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2015

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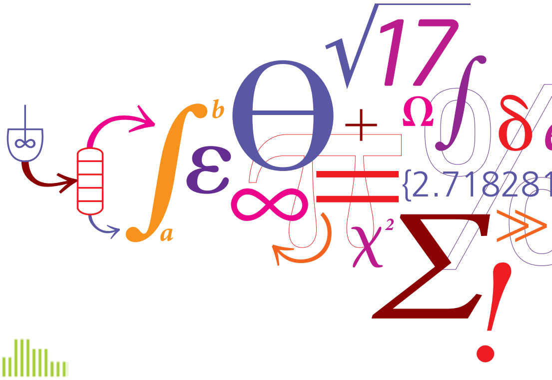

Ane Loft Mollerup

PhD Thesis

October 2015

DTU Chemical Engineering
Department of Chemical and Biochemical Engineering

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Preface

The thesis is organized in two parts: the first part puts the findings of the PhD into context in an introductive review; the second part consists of the papers listed below.

Paper I: **A.L. Mollerup**, P.S. Mikkelsen, D. Thornberg and G. Sin, 2015. Control system for sewer systems - a review of existing design frameworks in EU cities and the presentation of a time-scale dependent framework. *Urban Water Journal*. In revision.

Paper II: **A.L. Mollerup**, P.S. Mikkelsen, D. Thornberg and G. Sin, 2015. Regulatory control analysis and design for sewer systems. *Environmental modelling and software*, 66, 153-166

Paper III: **A.L. Mollerup**, P.S. Mikkelsen and G. Sin, 2015. A methodological approach to the design of optimisation and control strategies for sewer systems. In preparation.

In the thesis the scientific papers are cited as e.g. (Paper II).

In addition, the following publications, not included in this thesis, were also concluded during this PhD study:

- **A. L. Mollerup**, M. Mauricio-Iglesias, N. B. Johansen, D. Thornberg, P. S. Mikkelsen and G. Sin, 2012. Model-based analysis of control performance in sewer system, *Proceedings of the 17th Nordic Process Control Workshop, Kgs. Lyngby, Denmark*, 123-127.
- **A. L. Mollerup**. Brugen af nedbørsmålinger i styringen af spildevandssystemet. *Teknisk rapport 14-03, Drift af Spildevandskomitéens Regnmålersystem, Årsnotat 2013*, 37-42.
- **A. L. Mollerup**, M. Grum, D. Muschalla, E. van Velzen, P. Vanrolleghem, P. S. Mikkelsen and G. Sin, 2013. Integrated control of the wastewater system: potential and barriers. *Water 21*, **15** (2), 39-41.
- **A. L. Mollerup**, P. S. Mikkelsen, D. Thornberg and G. Sin, 2013. 16 years of experience with rule based control in Copenhagen's sewer system. *Proceedings of the 2013 IWA conference on Instrumentation, Control and Automation (ICA), Narbonne, France.*
- M. Mauricio-Iglesias, I. Montero-Castro, **A. L. Mollerup** and G. Sin, 2015. A generic methodology for the optimization of sewer system using stochastic programming and self-optimizing control. *Journal of Environmental Management*, **155**, 193-203.
- V. Courdent, L. Vezzaro, P. S. Mikkelsen, **A. L. Mollerup** and M. Grum, 2015. Using ensemble weather forecast in a risk based real time optimization of urban drainage systems, *La Houille Blanche*, **2**, 101-107.

Acknowledgements

This project is initialized and financed by HOFOR and BIOFOS and is financially supported by The Danish Agency for Science, Technology and Innovation under the Industrial PhD program.

The PhD project was affiliated with the Storm and Wastewater Informatics (SWI) project (http://www.swi.env.dtu.dk). I thank all partners and colleagues in SWI for the collaborations in the project.

I would like to thank my supervisors; Associate Professor Gürkan Sin, Professor Peter Steen Mikkelsen, Dr. Niels Bent Johansen and Dr. Dines Thornberg, for valuable support and feedback during this PhD study. Our discussions on sewer system control have been inspiring and the support indispensable.

I would like to thank my colleagues at HOFOR for their support and encouragement and I would also like to thank Dr. Miguel Mauricio-Iglesias for his help on Matlab, Simulink and the application of control theory.

Finally I would like to thank my husband and family for supporting me. Without their love and support I would not have made it through.

Summary

When designing sewer system control, there is a lack of methodology and tools that can aid in the design process. In 2004 the PASST[1] framework was presented that focuses on determining the potential for control in sewer system operation. However, for the actual design of control systems urban drainage planners still have to rely on their operational knowledge combined with model simulations and trial and error. This is an inefficient process where the final design largely depends on the urban drainage planner's knowledge about the system dynamics and control in general. The motivation for this thesis was therefore the wish for a methodological approach to sewer system control design. Using a case study the following research hypothesis was tested in this thesis:

Using classical and modern control theory, a methodological approach can be derived for designing sewer system control. This can aid urban drainage planners and other professionals in the planning phase of sewer system control design and effectively contribute to find novel control solutions.

It was investigated if the established methodology used in classic control theory for process control design can be applied meaningfully to the sewer system. As the methodology takes its basis in a hierarchical decomposition of the control problem based on time-scale, it was also investigated if sewer system control can be decomposed in a similar manner.

From a review of existing control systems for sewer systems in Europe, it was concluded that sewer system control can also be decomposed in a hierarchical manner based on differences in time-scale. The proposed time-scale dependent hierarchy for sewer system control contains four layers that each handles their own dedicated task. From the bottom and up they are: 1) the regulatory control layer, 2) the coordinating control layer, 3) the optimisation layer and 4) the management of objectives layer.

The time-scale dependent hierarchy for sewer system control is put into a framework that also contains a terminology related to control. In this way the

[1] Planning aid for sewer system real time control

framework can help to compare different control system solutions and facilitate a clear communication between different professions and disciplines working together in sewer system control design.

Starting from the hierarchical decomposition of sewer system control in layers, a stepwise approach to design sewer system control was proposed and followed. The individual layers of the hierarchy were designed one by one for a case study in Copenhagen, with the methods and tools taken from both classical and modern control theory.

The tools of classical control theory are developed for systems that can be approximated by linear models. The main challenge of using classical control theory on the case study was therefore the transient nature and the non-linearity of the sewer system dynamics. The methodology was adapted, by linearizing the sewer system model at various points in time, creating a step-wise linear model. The results of the linearization showed that the sewer system dynamics could be divided into four phases, characterised by the following operation modes: dry weather, filling, saturation and emptying. Having obtained a piece-wise linear model for each of the operational modes, the tools from classical control theory, such as the calculation of the condition number and the relative gain array, could be successfully applied to the sewer system. Based on the results a pairing between the measurement variables and the actuators could be suggested.

Having proposed to decompose the sewer system control in a hierarchical manner, it became necessary to investigate the role of the lowest layer in the hierarchy, which is the regulatory control layer. Traditionally the role of the regulatory layer is to reject disturbances and track the setpoints, and the simplest form of regulatory control has just constant setpoints. However, in a transient system like the sewer system, the setpoints may change dramatically and rapidly. Therefore the regulatory control layer may not have the same functionality when designed for the sewer system. From the application of the classical control theory it was found that the system dynamics could be described by four operational modes, and instead of a fixed setpoint the regulatory control layer needs changing setpoints, according to the operational modes. These can either be fed from a coordinating control layer or from an online optimisation.

To design an optimisation to feed setpoints to the regulatory control layer, modern control theory was applied to the case study. The optimisation was tested when it acted directly on the actuators and when it acted on the regulatory control layer. The two optimisation based control structures were evaluated from a one year simulation and the results showed that there was little difference in the performance. The optimisation based control structures were also compared to the existing control and the regulatory control with set-points coming from the coordinating control layer, and here the latter showed the best performance. This was not unexpected, since the true potential of having optimisation arises, when a system has many control loops with limiting constraints and/or changing prioritisation between them. The results showed that for small sewer systems, where the complexity is limited, it is not necessarily the best option to implement advanced optimisation based control systems. Therefore it is also advisable to approach the design of a control system in a methodological manner, where the design and evaluation can be done step by step.

Based on the experiences gained from designing sewer system control systems for the case study, a systematic methodology for designing sewer system control is proposed that combined the steps, control and optimisation tools and methods used throughout the thesis. The proposed methodology provides a basis for gathering experiences with sewer system control design and knowledge sharing; and will help generate control systems of the future that are more robust, more structured, have a better performance and are easier to maintain.

Dansk sammenfatning

Når man designer en styring til afløbssystemet mangler der en metodik og nogle værktøjer, der kan hjælpe i designprocessen. I 2004 blev PASST-værktøjet[2] præsenteret, der fokuserer på at bestemme potentialet for styring. For det reelle design må afløbsplanlæggere dog stadig sætte deres lid til viden om driften af systemet kombineret med model simuleringer, der bruges til at evaluere potentielle løsninger. Dette er en ineffektiv proces, hvor det endelige design i høj graf afhænger af afløbsplanlæggerens viden om dynamikken i afløbssystemet og om styring generelt. Motivationen for denne afhandling var derfor et ønske om en mere metodisk fremgangsmåde til design af styringer i afløbssystemet. Ved hjælp af et case studie blev følgende forskningshypotese undersøgt:

Ved brug af klassisk og moderne styringslære kan en metodisk fremgangsmåde til design af styringssystemer til afløbssystemet blive udledt. Dette kan hjælpe afløbsplanlæggere og andre fagfolk i planlægningsfasen af designet af styringssystemer til afløbssystemet og effektivt medvirke til at finde nye styringsløsninger.

Det blev undersøgt om den etablerede metodik, der benyttes indenfor klassisk styringslære til design af processtyringer, kan anvendes meningsfyldt på afløbssystemet. Da denne metodik tager afsæt i en hierarkisk opdeling af styringsproblemet baseret på tidsskala, blev det ligeledes undersøgt om styring af afløbssystemet kunne opdeles på samme vis.

Fra en gennemgang af eksisterende styringssystemer i afløbssystemer i Europa, blev det konkluderet, at styringer af afløbssystemet med fordel også kan opdeles hierarkisk baseret på forskelle i tidsskala. Det foreslåede tidsskalaafhængige hierarki for styring af afløbssystemer indeholder fire lag, der hver især står for udførelsen af deres dedikerede opgave. Fra bunden og opefter er de: 1) det regulerende lag, 2) det koordinerende lag, 3) det optimerende lag og 4) lag til håndtering af målsætninger.

[2] Planning aid for sewer system real time control (på dansk: Hjælp til planlægning af styring af afløbssystemet).

Det tidsskalaafhængige styringshierarki for styring af afløbssystemet er samlet i et rammeværktøj, der ikke blot beskriver hierarkiet, men også indeholder en terminologi relateret til styring. Dermed giver rammeværktøjet mulighed for bedre kommunikation mellem de forskellige grupper af fagfolk og discipliner, der arbejder sammen i designet af styring af afløbssystemer.

Med udgangspunkt i det tidsskalaafhængige hierarki blev en trinvis metode til design af styring af afløbssystemet etableret og fulgt. De individuelle lag i hierarkiet blev designet ét for ét for et casestudie i København, med metoder og værktøjer hentet fra både klassisk og moderne styringslære.

Værktøjerne fra klassisk styringslære er udviklet til systemer, der kan tilnærmes med lineære modeller. Den primære udfordring ved brugen af klassisk styringslære var derfor, at afløbssystemets tilstand er hurtigt skiftende og ikke kan beskrives ved en lineær sammenhæng mellem inputs of outputs. Problemet blev løst ved at linearisere modellen af afløbssystemet på en række forskellige tidspunkter i løbet af en simulering, hvorved man opnåede en stykvis-lineær model. Resultatet af lineariseringen viste, at dynamikken i afløbssystemet kunne opdeles i fire faser, der hver især var karakteriseret af tilstanden af systemet: tørvejr, fyldning, mætning og tømning. Med den stykvis lineære model til beskrivelse af de fire faser, kunne værktøjerne fra klassisk styringslære blive anvendt succesfuldt på afløbssystemet. Baseret på resultaterne kunne der foreslås en parring mellem målinger og aktuatorer.

Med forslaget om at dekomponere styringer af afløbssystemet i et hierarki, blev det nødvendigt tillige at undersøge, hvilken rolle det nederste styringslag har, hvilket er det regulerende lag. Traditionelt set har det regulerende lag til formål at afvise forstyrrelser og følge setpunkterne, og den simpleste form for regulerende styring har blot et fast setpunkt. Det er dog ikke sikkert, at det regulerende lag har samme funktionalitet i afløbssystemet. Dynamikken i afløbssystemet er hurtigt skiftende, hvorfor setpunkterne kan ændre sig både ofte og betydeligt i værdi. Fra anvendelsen af klassisk styringslære blev det konkluderet, at dynamikken i afløbssystemet kunne beskrives ved fire faser, og i stedet for et fast setpunkt har det regulerende lag brug for varierende setpunkter, i overensstemmelse med de fire faser. Disse kan enten komme fra et koordinerende styringslag eller fra en online optimering.

Til designet af en optimering, der kan sende setpunkter til det regulerende lag, blev moderne styringslære anvendt på case studiet. Optimeringen blev testet, både hvor den interagerede direkte med aktuatorerne og hvor den interagerede med det regulerende lag. De to optimeringsbaserede styringsstrukturer blev evalueret baseret på simuleringer af et års historiske regnserier. Resultaterne viste at der kun var lille forskel i det opnåede resultat. De to optimeringsbaserede styringsstrukturer blev ligeledes sammenlignet med den eksisterende styring og med det regulerende styringslag, hvor setpunkterne kom fra et koordinerende styringslag. Sammenligningen viste, at den sidstnævnte styring præsterede bedst. Dette var ikke overraskende, da det fulde potentiale for optimering opstår, når et system har mange styringsløkker med begrænsning og/eller har skiftende prioritering mellem styringsløkkerne. Resultaterne viste at for små afløbssystemer, hvor kompleksiteten er begrænset, er det ikke nødvendigvis den bedste løsning at implementere avancerede styringsløsninger baseret på optimering. Det er derfor tilrådeligt at tilgå designet af styringer i afløbssystemet ved hjælp af en metodisk fremgangsmåde, hvor designet of evalueringen kan udføres trinvist.

Baseret på erfaringerne opnået ved at designe styringssystemer til afløbssystemet i casestudiet, er det foreslået at kombinere de trin, værktøjer og metoder, der er brugt igennem afhandlingen i en samlet metodik til design af styringssystemet til afløbssystemet. Den foreslåede metodik danner et grundlag for indsamling af erfaringer med design af styringssystemer til afløbssystemer og vidensdeling på området; og vil hjælpe til at fermtidens styringssystemer i afløbssystemet bliver mere robuste, virker bedre og er lettere at vedligeholde.

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Abbreviations and terms

The abbreviations found below are used throughout the thesis. They are presented by the full name the first time encountered in the thesis and afterwards referred to by the abbreviation.

Abbreviation	Full name
CDS	Chicago design storm
CLABSA	Clavegueram de Barcelona
CN	Condition number
CSO	Combined sewer overflow
CV	Controlled variable
DMI	Danish meteorological institute
f.d.RGA	Frequency dependent relative gain array
HOFOR	Copenhagens utility company (in Danish: Hovedstadsområdets forsyningsselskab)
MeV	Measurement variable
METSAM	Environmentally efficient technology to integrated control between sewer system and wastewater treatment plant (in Danish: Miljøeffektiv teknologi til samstyring af afløbssystem og renseanlæg)
MIMO	Multiple input – multiple output
MPC	Model predictive control
MV	Manipulated variable
ODE	Ordinary differential equation
OMOVAST	Operational model for early warning and control (in Danish: Operativ model til styring og varsling)
PASST	Planning aid for sewer system real time control
P-controller	Proportional controller
PID	Proportional integral derivative
PRGA	Performance relative gain array
RGA	Relative gain array
RTC	Real time control
SISO	Single input – single output
SVK	The Water Pollution Committee of The Society of Danish Engineers (in Danish: Spildevandskomiteen)
SWI	Storm- and wastewater informatics
VT	Virtual tank
WWTP	Wastewater treatment plant

1 Introduction

The first sewer systems were constructed more than 150 years ago. At that time the main purpose was to transport the sewerage and rainwater from the city centres to the nearby receiving waters to ensure public health.

Since then much has changed; the focus today is not only on public health but also on the environment. The sewer systems have been expanded and connected to wastewater treatment plants (WWTPs), to ensure that the receiving waters are protected against pollution as much as possible.

However, the cities are still growing, the legislation is getting continuously tightened, and the predicted effects of climate change on the precipitation patterns are changing the design criteria as we know them. Wastewater utilities need to find ways to handle larger volumes and flows of wastewater and storm water, while at the same time reducing the discharge of pollutants to the receiving waters.

For wastewater utilities there are in general three ways to deal with this challenge: 1) Expand the existing structures, 2) intercept the storm water and redirect it or use it locally, such that it is not mixed with the sewerage, 3) improve the performance of the existing systems through the implementation of control. The first option is an expensive alternative and in dense cities there is also a lack of available space for such structures. The second option can also be expensive, but the limitations are more often due to problems with regulations and coordination with other stakeholders. The third alternative, implementing a control system, doesn't require new structures and though sometimes expensive, it can prove a cost-efficient solution. By adjusting the operation to the changing conditions (e.g. redirecting the wastewater to unused parts of the sewer system) the efficiency of the wastewater system can be improved; often with only little additional effort, compared to a conventionally operated system (Dircks et al. 2011 and Beeneken et al. 2013).

Many combined sewer systems can improve the performance, with respect to combined sewer overflow (CSO) from the system, through the implementation of control. Some sewer systems are merely not designed ideally, as the fight for suited locations in bigger cities force the wastewater utilities to construct storage volumes were it is possible instead of where it would have the best effect. However, even older systems that originally had an ideal design can also have potential for control. The reason for this is that a sewer system is designed according to a certain rainfall distribution and catchment properties. However, rainfall is stochastic in nature with respect to both its distribution and intensity, and therefore the design load of the sewer system is rarely met. Moreover, the catchment properties change over time, and together these two factors often create a potential for control. The state of the art in sewer system control and the potential related to the implementation of control in the sewer system was highlighted more than 25 years ago by Schilling (1989). Since then numerous papers have been published on sewer system control. Still, in 2004 a paper on the status of sewer system control was published (Schütze et al. 2004a), where it is stated that the majority of sewer systems still have only little or no control, with the exception of some sophisticated case studies.

Since then the number of interesting case studies has increased (e.g. Langeveld et al. 2013, Mollerup et al. 2013, Seggelke et al. 213, Vezzaro et al. 2013). Yet it seems that few wastewater utilities have implemented sewer system control to improve systems performance, as the number of publication on experiences with sewer system control design and implementation in practice is still very limited.

One of the reasons for this could be the lack of a common terminology and framework for describing sewer system control. In Schütze et al. (2004a) the authors stress the need for "a clear terminology to enable better cooperation of scientists and experts of different areas relevant to RTC[3]". Despite this statement being more than ten years old, the terminology related to sewer system control still does not contain sufficient details to easily and accurately describe different control structures and control techniques. Still, all types of control systems in sewer systems are called real time control (RTC), making it difficult to search out and compare relevant control solutions. Therefore, there is a need for a more comprehensive terminology and framework to describe sewer system control systems.

Another reason is the lack of a methodology and tools for designing sewer system control. In 2004 the PASST[4] framework was presented (Schütze et al. 2004b). This framework focuses on determining the potential for control.

[3]RTC = Real Time Control

[4] PASST = Planning aid for sewer system real time control.

However, for the actual design urban drainage planners still have to rely on operational knowledge combined with model simulations and trial and error. This can be an inefficient process where the final design largely depends on the urban drainage planners' knowledge about the system dynamics and control in general.

An approach to process control design which is widely used in the field of control engineering (Larsson and Skogestad 2000), including wastewater treatment engineering (Olsson and Newell 1999, Vangsgaard et al. 2014), is the process oriented approach. This approach employs a set of tools and methods from control and systems theory. It follows a step-by-step procedure to design the regulatory control, through the definition of the control objective, screening of measurements, assessment of measurement sensitivities to changes in the inputs and pairing between measurements and inputs, also known as a controllability analysis. Using this information the control loops are formulated, i.e. the decision about the pairing of controlled variables with the manipulated variables is done and evaluation of promising control loops is made.

It is the hypothesis of this thesis that the process oriented approach can be adapted to sewer systems, and valuable insight can come from applying it to sewer systems. If possible, it can form the basis of a stepwise approach to sewer system design. However, adapting the methods and tools used in the process oriented approach for control system design (tailored for the needs of process dynamics and operations in chemical and wastewater treatment engineering) to sewer system is not straightforward and requires a systems analysis approach. The main challenge in sewer system operation is the fact that the disturbances, mainly the rainfall runoffs, are highly stochastic and transient in nature which creates transient dynamics in the sewer system that cannot be captured by linear models. Nevertheless, the tools from classic control theory are in principle generic and may still provide insights into the analysis of sewer systems operation and control; provided that the methodology is adapted to the specific needs of sewer system control.

1.1 Research objectives

The motivation for this thesis is to develop a methodological approach to sewer system control design. The aim is to form a complete framework for sewer system control design. Part of that is to develop a common terminology, so as to minimise the risk of misunderstandings, as some terms have different meaning in the field of process control and sewer system control (e.g. integrated control, supervisory control).

An established methodology exists in classic control theory for process control design, which is used in the design of wastewater treatment plant control. Therefore it seems natural to investigate if this methodology can be applied meaningfully also to the sewer system.

As the methodology takes its basis in a hierarchical decomposition of the control problem based on time-scale, part of the objective of the thesis is to investigate if sewer system control can be decomposed in a similar manner.

In a hierarchical control system, the role of the lowest layer, also called regulatory control, is to reject disturbances and track setpoint trajectories. However, in a transient system like the sewer system, the lowest control layer may not have the same functionality, as the sewer system actuators are not designed to fully reject the disturbances. The role of the lowest control layer in sewer system control should therefore be investigated.

Therefore the research hypothesis of this thesis is:

Using classical and modern control theory, a methodological approach can be derived for designing sewer system control. This can aid urban drainage planners and other professionals in the planning phase of sewer system control design and effectively help to find novel control systems for their particular system.

The research objectives of the thesis are defined as follows:

1. To propose a common terminology for sewer system control and operation.
2. To investigate if sewer system control can be decomposed in a hierarchical manner with respect to time-scale.
3. To examine if and how the methods and tools for process control design can be applied to the sewer system.
4. Investigate the interactions between the control layers of the hierarchy, when applied to a sewer system.
5. Develop, test and validate a methodology for step-wise design of sewer system control.

1.2 Outline

This thesis is divided in two parts. Part I is a report, which provides the background for the thesis; it introduces and summarizes the most important results of the papers listed in the preface. Part II is a collection of those papers.

Part I is structured as follows:

Chapter 2 presents a framework for describing sewer system control, including terms and definitions related to control used in this thesis.

Chapter 3 presents the work done on designing sewer system control; the case study is presented and the tools and results are shown and discussed. The chapter is divided into six parts that relate to the different steps in the design procedure. The experiences with designing sewer system control are summarised in the last section, where also a methodology for the design of sewer system control is proposed.

In Chapter 4 the results are summarised and the research questions are answered.

In Chapter 5 the results are put into perspective; both with respect to closely related projects and potential future work.

Chapter 6 contains the references in alphabetical order

2 Framework for describing sewer system control

In this chapter the terminology and definitions related to control are presented. Also a time-scale dependent hierarchy for sewer system control is presented.

2.1 Terms and definitions

An *actuator* is a controllable device such as a pump, gate, valve, etc. Actuators are the manipulated variables.

Manipulated variables (MV) are those variables that can be adjusted by the control.

Measured variables (MeV) are the variables that are measured by means of sensors such as level meters, flowmeters, rain gauges, etc.

Controlled variables (CV) are the variables that are controlled. For example, water level in a tank or flow in a pipe.

S*etpoints* are the desired values of the controlled variables.

Control is the adjustment of available degrees of freedom to assist in achieving acceptable operation of the system (Larsson and Skogestad, 2000). In a sewer system that means finding out how to operate the actuators such that the setpoints of the control are met and disturbances are rejected.

A *disturbance* to the system is any input to the system, which affects the controlled variables, but cannot be manipulated. For a sewer system that is the rainfall runoff and the sewerage. Consider the example of controlling the water level in a tank. In this example, to *reject a disturbance* means that the water level in the tank (the controlled variable) is kept at its fixed setpoint value, despite varying inflow (disturbance to the system) by adjusting (controlling) the outflow from the tank, using a proper control technique.

The *control technique* is the control law or method used to calculate the adjustment of the manipulated variable such as PID[5], MPC[6], rule based, etc.

The *controller* contains the control technique and calculates the correcting action of the actuator.

A *control loop* consists of a system (or unit) to be controlled; a sensor, a controller and an actuator.

If a controlled variable can be kept at the desired setpoint by adjusting a single manipulated variable, the control loop has a single input and a single output and is therefore called a *single-input, single output (SISO) control loop*.

If two or more individual control loops are interacting, both have to be adjusted simultaneously and in a coordinated fashion to obtain the desired setpoints. This control configuration is called *multiple-input, multiple-output (MIMO) control* or *multivariable control*. With multivariable control the control actions of all the actuators in the loop are calculated with one control algorithm.

*Centralised contro*l relates to the architecture of the implemented control system. With centralised control there is a single optimizing controller which both stabilises the system processes as well as perfectly coordinates all the manipulated variables (Larsson and Skogestad, 2000). However, for large systems it is often not possible to design such a controller. Instead the control is decomposed in "blocks" in either a vertical way (*hierarchical*) or horizontal way (*decentralised* or *distributed control*) (Larsson and Skogestad, 2000). The typical way of controlling the sewer system is in a decentralised way, with the control being distributed into local controllers (SISO control loops) (Alex et al. 2008).

The *control system* is the entire architecture of blocks, when the control is decomposed (Larsson and Skogestad, 2000).

Control system design can be divided into three activities: 1) Control structure design, 2) Controller design, and 3) Implementation.

[5] Proportional Integral Derivative

[6] Model Predictive Control

The control system is designed to aid the *operation* of the system. *Operability* is the ability of the system (together with its control system) to achieve acceptable operation (Larsson and Skogestad 2000).

Control structure design is the five tasks of selecting controlled variables, selecting manipulated variables, selecting measurements, selecting control configuration, i.e. the structure that connects measurements, controlled variables and manipulated variables and selecting the *control techniques*, i.e. the specification of the control techniques (Larsson and Skogestad 2000).

Integrated control is a control system that looks at the entire wastewater system, from sewer system to WWTP, and potentially also the receiving water body, with respect to the measurements used and the control objectives (Butler and Schütze 2005).

Plant-wide control is a concept, commonly applied, to process plants like WTTPs (Olsson 2012). The purpose of plant-wide control is to ensure that the individual control loops are not conflicting, while the overall objective of the plant is met. This is done by breaking down the control problem into a hierarchy based on time-scale, where the individual layers have each their own task (see Figure 1).

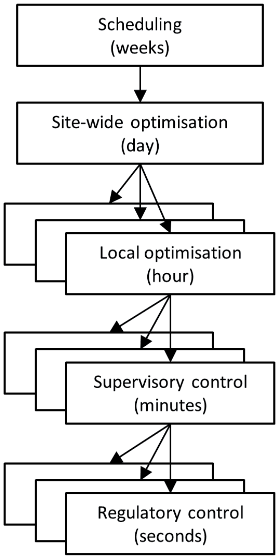

Figure 1: Typical control hierarchy in a chemical plant with plant-wide control (Larsson and Skogestad 2000).

2.2 Timescale dependent control hierarchy

Sewer system control today is typically decomposed horizontally, based on a spatial decomposition. What this means is that the control problem is split into sub-problems that are managed locally. In the field of urban drainage this is also called local control (Schütze et al. 2004a) and from a systems perspective it is called distributed or decentralised control (see previous section). However, if the sub-problems are in reality interacting, this type of decomposition can prove sub-optimal; and trying to optimise it by adding logic switches or cascading feedback loops can result in a complex and confusing control system. Another method for decomposing the control problem is vertically as shown in Figure 1. In this way the interactions are managed, while the complexity of the control problem is reduced by dedicating the individual layers in the hierarchy to different tasks (e.g. track setpoints, decouple interacting control loops, determine the setpoints).

In WWTP control it is a well-established idea to use plant-wide control as the framework for describing and designing the control system (Olsson an Newell 1999). When moving towards integrated control between sewer systems and WWTPs it is therefore considered a benefit for the field of urban water management, if the hierarchy could be extended to the sewer system control. However, WWTPs operate with continuous processes that can be described by linear models, which the sewer system cannot. Since the sewer system dynamics are stochastic and transient in nature and cannot be described by linear models, the framework cannot be directly transferred, but needs to be adapted.

Based on an investigation of three different sewer system control systems in Europe, together with a review of other existing control hierarchy frameworks, a time dependent control hierarchy for sewer system control was proposed in Paper I. What separates this framework from those previously proposed for sewer systems is the focus on the frequency with which the calculations are updated and the information exchanged between the layers of the hierarchy. In Figure 2 a suggestion for a timescale is made. The frequencies of action at the individual layers are specified as ranges, since these can be different for different sewer systems, depending on the number of layers and how fast the transients and responses of the system are. The layers are linked by information passed on between the higher and the lower layers.

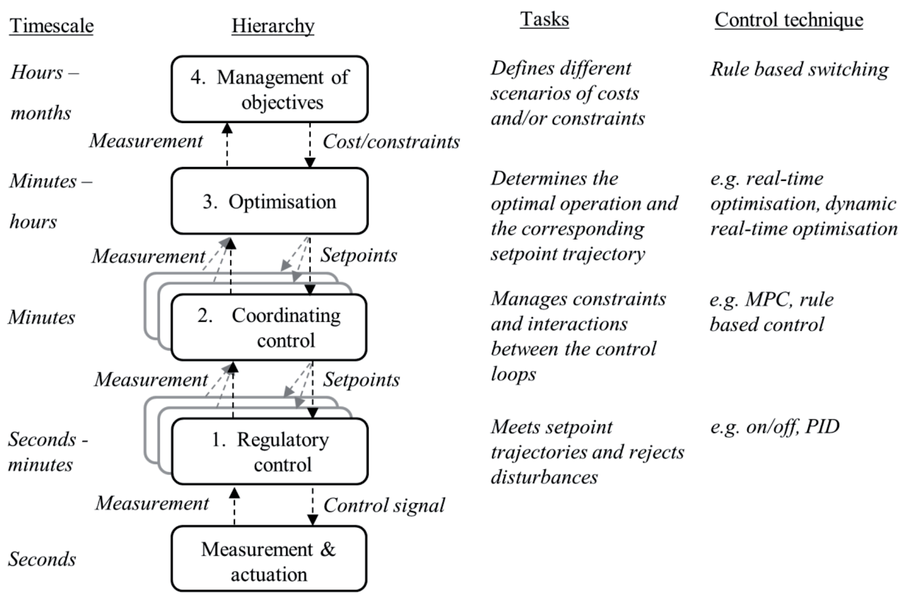

Figure 2: Time dependent control hierarchy for sewer systems (Paper I).

Layer 4: Management of objectives. At the very top of the hierarchy is the management of objectives layer, which defines the overall scope and targets for the sewer system operation that may take into account legislative requirements as well as operational objectives. Here constraints and costs used for the objective function in the optimisation are specified. Changes to the constraints and costs could be due to seasonal changes, such as being in or out of the bathing season or a diurnal pattern of changing cost of electricity. Though no known control system for a sewer system have implemented a structure with such a layer today, it is included in the hierarchy as it naturally complements the control hierarchy and may become relevant in a near future. For example CLABSA[7], the wastewater utility in Barcelona, has found that in their case the two primary objectives, avoiding flooding and minimising CSOs, work against each other, and it has not been possible to tune the weighting of these to have a dynamic prioritisation. Avoiding flooding will always be the dominant term in the objective function. As a result they are thinking about including the management of objectives layer in their new control system, which will enable them to switch between prioritising the two objectives, depending on the forecasted rainfall (Paper I). In this way the optimisation formulation is no longer continuous, but becomes event driven.

Layer 3: Optimisation. The task of the optimisation layer is to determine the optimum operation and the desired setpoints or setpoint trajectories for the control layers. This can be done online or offline, but in a sewer system the states change frequently and rapidly during a rain event. Therefore a setpoint will only be optimal for a short period of time. As a result the setpoint will have to be updated very often, or instead of a single value the optimisation could provide a trajectory of setpoints.

Layer 2: Coordinating control. Below the optimisation layer there can be a coordinating control layer. In plant-wide control the coordinating control layer is the called supervisory control layer. However, in sewer system control supervisory control has a different meaning; there it is used to describe the level of automation of the control system (Schütze et al. 2004a). Therefore, the layer has been named the coordinating control layer.

[7] Clavegueram de Barcelona (CLABSA).

The coordinating control layer is needed if the control loops are interacting or there are some constraints on either the manipulated or the controlled variables that cannot be violated. In a sewer system the primary constraints are often on the capacity of the actuators, but they could also be on the flow or water levels at key locations in the sewer system. The role of the coordinating control layer is to decouple interacting control loops and manage constraints. In practice this layer will rarely be implemented as a separate layer. Instead it is often seen embedded directly in the controllers along with the regulatory control, or the constraints are managed in the optimisation.

Layer 1: Regulatory control. The lowest layer controller is the regulatory control layer. The regulatory control layer ensures that the setpoints or trajectories are followed, and that the disturbances are rejected.

Since each layer acts at different timescales, the actions at the higher layers are discrete. This means that the system will never be able to achieve a truly optimal operation, since that would acquire a continuous determination of the optimum setpoints (Larsson and Skogestad 2000). For a steady-state system the determination of the timescales are important and relates to frequency of the disturbances acting on the system as well as the rate of change of the constraints and costs (e.g. number of orders, cost of materials, available manpower, etc.). As the determination of the timescales is important for a steady state system, it seems reasonable to extrapolate that this will be especially true for a system with a transient nature like that of the sewer system. The implication is that the choice of timescale becomes a balancing act. Either the optimal behaviour is approximated through frequent updating of setpoints, requiring the computation of these to be fast, which makes demands on the used techniques. Or the setpoints are determined from more optimal, but also more time consuming techniques, which makes demands on the updating frequency.

A point of discussion is the role of the coordinating layer. It is defined as the layer where interacting control loops are decoupled and constraints are managed. It can be argued that in practice these tasks are usually handled by the optimisation or by rule-based control embedded in the regulatory control layer, and the layer should therefore be omitted. On the other hand, to base a generic control hierarchy only on current examples of sewer system control reported in literature could quickly prove limiting. Most sewer system control implemented today focus on the quantitative aspects of CSO, whereas research is also focusing on the qualitative aspects of CSO (e.g. Vanrolleghem et al. 2005, Langeveld et al. 2013). The hierarchy is therefore kept as generic as possible to maintain the maximum of flexibility, such that hopefully it can also handle the sewer system control hierarchies of the future.

The value of the time-scale dependent framework lays in its ability to visualise control structures in a manner that enables a comparison between them. This can be of value in the design phase, but will also continue to be of value in the proceeding development of the system. Having the control structure documented will enable the utility company to not only compare the system with others, but also help them in the maintenance and further development of the control system, which is an important often neglected aspect after implementation. By applying the framework in detail, an inventory is provided of the control loops and the control techniques used in the control system and at which layer in the hierarchy they are applied. This is helpful when pinpointing if and where updates are needed, and where to begin when evaluating the control system. It is also helpful as a communication tool, to set the stage for collaboration between experts from a very broad range of fields that are involved when designing sewer system control systems of the future (e.g. environmental engineers, chemical engineers, hydrologists, electrical engineers, control engineers), since each of these often haven their own terms and definitions.

3 Designing sewer system control

For the design of sewer system control, the control hierarchy presented in Figure 2, page 11 is taken as the starting point for control system design. In the following the control layers are designed one by one for a case study, starting at the bottom and moving up though the hierarchy.

3.1 Case study description

The case area is a sub catchment of Copenhagen's sewer system owned and maintained by HOFOR[8]. It has a size of 320 hectare (impermeable area) and is equipped with three pumping stations, two storage tanks, one pipe basin and five CSO structures (see Figure 3). The disturbances to the system are the sewerage (dry weather flow) and the rainfall runoff.

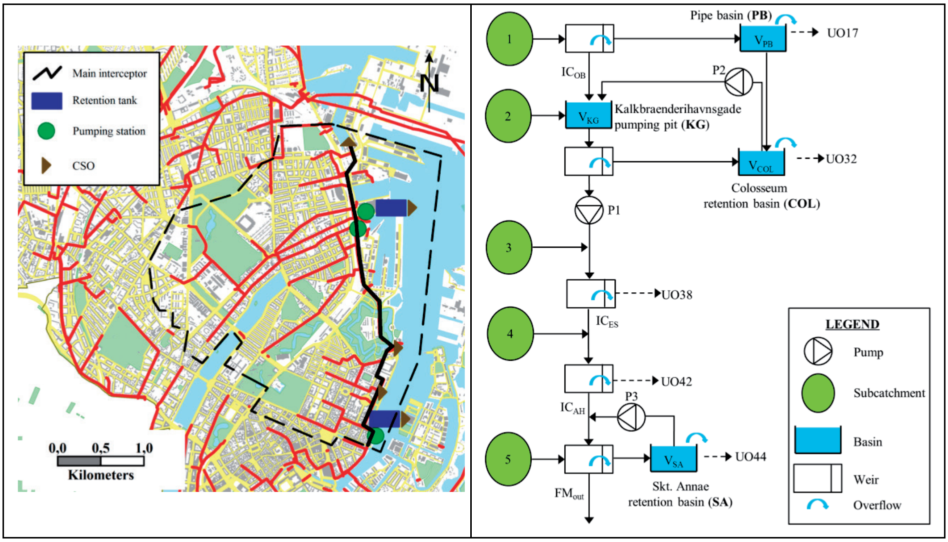

Figure 3: Case study. To the left: A map of the area (Paper II). To the right: A schematic representation of the sewer system.

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8 Danish: Hovedstadsområdets Forsyningsselskab, English: Copenhagen Utility Company. www.hofor.dk.

In Table 1 some key characteristics of the case study are shown.

Table 1: Key characteristics of the case study. The abbreviations are found in Figure 3, right.

Sub catchments	**1**	**2**	**3**	**4**	**5**
Area [reduced ha]	23.5	222.5	30.0	8.2	33
Dry weather flow [l/s]	29	1035	178	200	2
Retention basins	**PB**	**KG**	**COL**	**SA**	
Volume [1000 m^3]	0.61	1.60	35.72	7.05	
Interceptor pipes	**IC_{OB}**	**IC_{ES}**	**IC_{AH}**	**FM_{out}**	
Full running capacity [l/s]	400	900	1000	1000	
Pumps	**P1**	**P2**	**P3**		
Maximum capacity [l/s]	900	500	300		

The existing control is rule based, and has been developed over time as insights have been gained on the dynamics and interactions by the operators (from internal documents describing the controls in HOFOR). The pumping stations emptying the two basins, P2 and P3, are activated based on the level of water in the respective basins and their downstream water levels. The pumping station P1 elevates the wastewater, so it can continue to run by gravitation towards the WWTP. The control technique used at P1 is a PID[9] controller. The PID control is combined with a selective control mechanism, constraining the controlled variable, u; in this case the outflow from the pumping station. This has been done to ensure that the flow from the pumping station does not exceed the downstream capacity. The selector chooses the minimum value of the output from the PID controller and three alternatives. All three alternatives are based on downstream conditions. The first two seek to limit the flow to the CSO structure UO38, to minimize the risk of overflow, based on level measurements at or close to UO38. The last alternative value sent to the selector, comes from the retention basin at Skt. Annæ. This is because the Skt. Annæ basin empties (via P3) to the same interceptor

[9] Proportional Integral Derivative (PID).

pipe as P1. Therefore, there is known to be a limited capacity of this interceptor pipe during the emptying of Skt. Annæ.

The objective of the controls is to minimise the CSO volumes at the individual locations, as well as the total CSO volume. The individual CSO volumes can be calculated from:

$$\boldsymbol{UO}_h = \sum_{j=1}^{J} \boldsymbol{UO}_{h,j} \qquad \text{eq. (1)}$$

where J is the number of observations, h represents the external overflow locations and $\boldsymbol{UO}_{h,j}$ are the external overflow observations.

The total CSO volume can hence be calculated from:

$$\boldsymbol{CSO} = \sum_{h=1}^{H} \boldsymbol{UO}_h \qquad \text{eq. (2)}$$

where H is the number of external overflow locations.

The case study is a small part of the sewer system in Copenhagen. It is therefore assumed that rainfall falls homogenously over the whole catchment. The time of concentration in the system is mainly related to the runoff routing. However, there is also a significant in-system delays as the transportation time from Kalkbrænderihavnsgade Pumping Station (P1) to Esplanaden (IC_{ES}) is around 10 minutes.

3.2 Designing a regulatory control layer

As indicated in Figure 2 the regulatory control is the lowest control layer in the hierarchy. It ensures that the setpoint trajectories are met by adjusting the actuators. This is shown in Figure 4, where the difference between the measured values, and the setpoints are calculated and based on these the actuators are adjusted, to eliminate the difference. This is also called feedback control.

To design the regulatory control layer one needs to determine where to measure, what to control, which control techniques to use and the source of the setpoints.

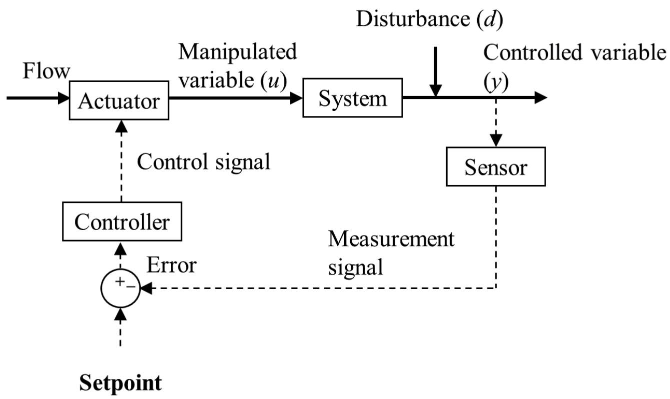

Figure 4: Feedback control loop

In Paper II the aim was to design a regulatory control layer that is efficient. Thus there should be minimum interactions between the different control loops of manipulated and controlled variables, while still maintaining a high sensitivity between the controlled variable and the manipulated variable of the individual control loops. The design of the regulatory control layer takes its basis in the process oriented approach (Seborg et al. 2011). The steps are shown in Figure 5.

The following sections will go through the methods and tools of the individual steps, as well as the results from applying them to the case study.

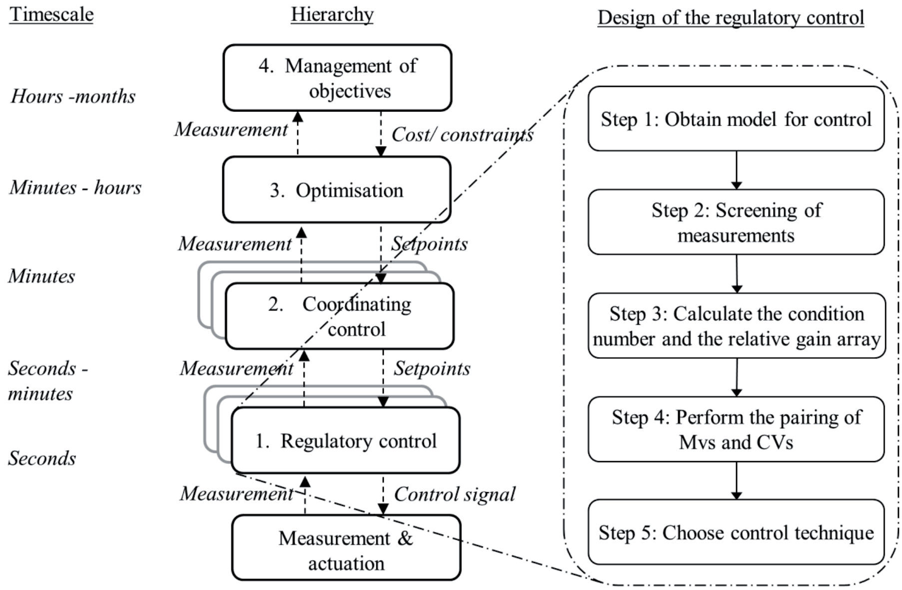

Figure 5: Steps in designing the regulatory control layer.

3.2.1 Obtain model for control

A virtual tank (VT) model (Ocampo-Martinez 2010) of the case study is presented in Paper II. Figure 6 shows a schematic representation of the model of the case study implemented in Matlab/Simulink. The VT model is a simple mass balance model using ordinary differential equations (ODE) to describe the change in volumes.

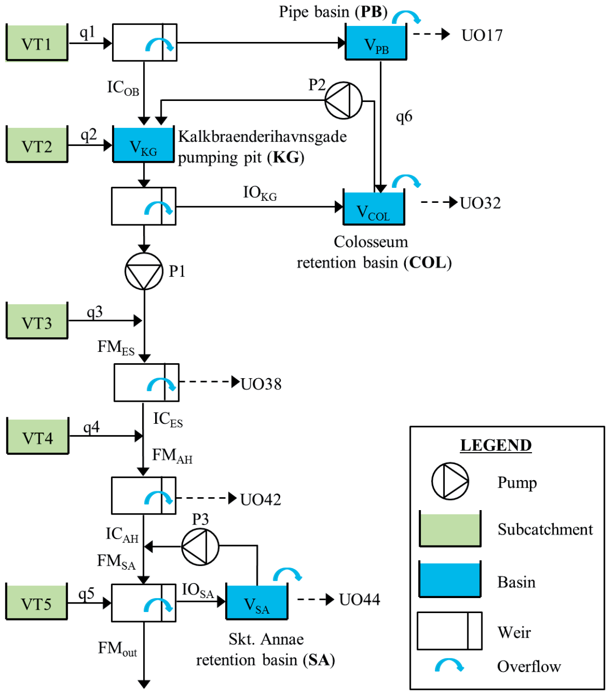

Figure 6: Schematic representation of the virtual tank model of the case study area. The abbreviations used are: VT = Virtual tank, P = pumping station, UO = External overflow, IO = Internal overflow, FM = Flow measurement, IC = Interceptor.

However, many tools from classical control theory need a transfer function model that describe the relationship between the inputs ($\boldsymbol{u}_i$) and the outputs ($\boldsymbol{y}_i$) of the system through a gain matrix (Seborg et al. 2011). As the system dynamics are important to consider, when analysing sewer system operation, the transfer function gain matrix is preferred to the steady-state gain matrix. The first step is therefore to translate the VT model into a transfer function gain matrix.

A gain matrix transfer function model is depicted in Figure 7, where $G(s)$ is the transfer function gain matrix that represents the system dynamics in the Laplace domain (frequency domain). To work in the frequency domain is chosen, because of the rich classical control toolbox available that offers tools and methods for controllability analysis.

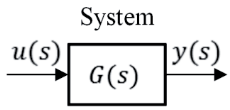

Figure 7**:** Transfer function model in the Laplace domain (Paper II).

For a dynamic system the transfer function model in the Laplace domain can be expressed in vector-matrix notation as:

$$\boldsymbol{Y}(s) = \boldsymbol{G}(s)\boldsymbol{U}(s) \quad \text{eq. (3)}$$

where $\boldsymbol{Y}(s)$ is the output matrix, $\boldsymbol{G}(s)$ is the transfer function matrix, $\boldsymbol{U}(s)$ is the input matrix and s is the Laplace variable.

In the time-domain, the input and output dynamics are represented by the state-space formalism as follows: (Seborg et al. 2011):

$$\frac{d\boldsymbol{x}}{d\boldsymbol{t}} = \boldsymbol{Ax} + \boldsymbol{Bu} \quad \text{eq. (4)}$$

$$\boldsymbol{y} = \boldsymbol{Cx} + \boldsymbol{Du} \quad \text{eq. (5)}$$

where $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ are matrices, $\boldsymbol{x}$ are the states, $\boldsymbol{u}$ are the inputs and $\boldsymbol{y}$ are the outputs.

The relationship between the state-space representation and the transfer function model follows (Seborg et al. 2011):

$$\boldsymbol{G}(s) \triangleq \boldsymbol{C}[s\boldsymbol{I} - \boldsymbol{A}]^{-1}\boldsymbol{B} \quad \text{eq. (6)}$$

where I is the identity matrix.

The state-space formulation is obtained from linearization of the VT model. The challenge is to describe the non-linear sewer system dynamics with a linear model. To overcome this obstacle the linearization is performed at different points of operation throughout the simulation of a Chicago Design Storm[10] (CDS) (Keifer and Chu 1957). The return period for the rain event is chosen to be between the known return period for the overflows, which is

[10] The CDS rain is obtained from the Danish regional intensity-duration-frequency relationships (Arnbjerg-Nielsen *et al.* 2002; Madsen *et al.* 2009).

approximately ½ year, and the return period for surface flooding, which is ten years. The return period for the rain event is therefore selected to be five years (T = 5 y)[11], to be certain the system saturates and overflows occur, as the model should also reflect these. In this way a piece-wise linear model is obtained. This is shown in Figure 8.

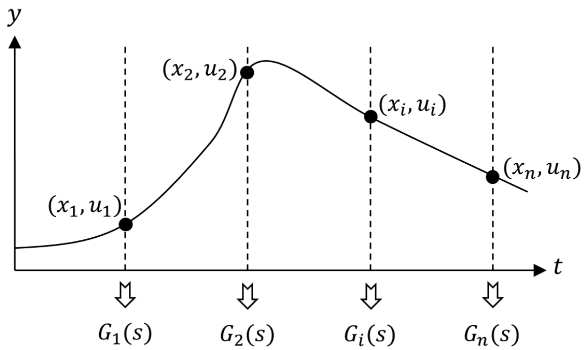

Figure 8: Conceptual representation of how the transfer function model is obtained at different operating points (Paper II).

Next the state-space formulation is converted to the Laplace domain, and the transfer function model is obtained. However, the classical control tools for controllability analysis are based on the gain matrix. Therefore the transfer function model needs to be evaluated at a certain operating point, s:

$$\boldsymbol{G_s} = \boldsymbol{Y}_s / \boldsymbol{U}_s \qquad \text{eq. (7)}$$

where $\boldsymbol{Y}_s$ and $\boldsymbol{U}_s$ are the output and the input, respectively, at a certain operating point s.

Selection of an appropriate input frequency to evaluate the system input-output dynamics is important, since it affects the sizes of the gains. Since rain events are stochastic in nature, there is no dominant frequency in the input disturbances (Mauricio-Iglesias et al. 2015). As this is the case, the knowledge of the dynamics of the system is used to determine a suitable fre-

[11] The duration of the rain event was set to four hours and the shape as symmetrical, resulting in a maximum intensity of 16.74 µm/s

quency. In the design or retrofitting of a sewer system using the Rational method, the dimensioning is based on the maximum, average intensity over the critical time span; with the critical time span being determined from the time of concentration (flow time in the system) (Winther et al. 2011). Based on a similar approach the frequency is chosen as the shortest critical time of concentration for the locations of the three actuators. This corresponds to the inverse of the largest flow conversion coefficient for the virtual tanks, $\beta_3 = 0.1036\ 1/\min$ (= 9.65 min). In the frequency domain this corresponds to 0.65 rad/min.

Having obtained the gain matrix, the gains are finally scaled, by dividing each input and output by its corresponding range (Seborg et al. 2011), to ensure the gains have comparable units.

The end result is a series of gain matrices, one for each point of linearization. Based on these, four different phases of the operation were identified in Paper II: dry weather, filling, saturation and emptying. Within each of these four phases the linear model is the same (Paper II). The resulting gain matrix can be seen in Table 2.

Table 2: Scaled gain matrix model of the case study (Paper II, supplementary data. The names of the variables correspond to those used in Figure 6.

	Dry weather (t = 0 - 45)			**Filling** (t = 75 - 165)			**Saturation** (t = 195 - 225)			**Emptying** (t = 465 - 2500)		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
FM_{ES}	0.20	0	0	0.20	0	0	0.20	0	0	0.20	0	0
FM_{AH}	0.62	0	0	0.62	0	0	0.62	0	0	0.62	0	0
FM_{SA}	0.18	0	0.06	0.18	0	0.06	0.18	0	0.06	0.18	0	0.06
UO32	0	0	0	0	0	0	-0.21	3 e-12	0	0	0	0
V_{COL}	0	-0.001	0	-0.002	-4 e-13	0	0	0	0	0	-0.001	0
IO_{KG}	0	0	0	-0.09	0.05	0	-0.09	0.05	0	0	0	0
V_{KG}	-0.05	0.03	0	0	0	0	0	0	0	-0.05	0.03	0
V_{SA}	0	0	-0.004	0	0	-0.004	0	0	0	0	0	-0.004
FM_{out}	0.90	0	0.30	0.90	0	0.30	0.90	0	0.30	0.90	0	0.30

From Table 2 it can be seen that actually the gain matrix is the same during the dry weather and emptying phase. However, the existing rule based control also operate with similar phases, and based on this it was decided not to merge the dry weather and the emptying phases, despite the gain matrices being the same.

3.2.2 Screening of measurements

Once the gain matrix is obtained it can be used for a sensitivity based screening, to eliminate measurement variables (MeV) that are not sensitive to changes in the manipulated variables (MV).

$$\mathrm{SA} = \frac{\partial \mathrm{MeV}}{\partial \mathrm{MV}} \qquad \text{eq. (8)}$$

If the MeV is not sensitive to changes in the MV then SA is equal to zero, and the MeV can be eliminated as a potential controlled variable (CV) candidate in any of the further investigations.

The preliminary screening can be used in two different ways: 1) only available measurements are included, 2) possible new sensor locations are also included. In Paper II the second approach is used, including all possible sensor locations. This was chosen since the installation of a new sensor is a relatively small investment, compared to installing a new gate, pump or basin.

The preliminary screening of measurements not sensitive to changes in the manipulated variables reduces the number of possible pairings to further investigate from 286 to 35 (Paper II). Several measurements are eliminated altogether, including most of the overflow measurements, which indicate that many of the overflows cannot be affected by the control.

3.2.3 Calculation of the condition number and the relative gain array

To analyse the measurements with respect to their use in control a controllability analysis is performed, whit the calculation of the condition number (CN) and the relative gain array (RGA).

The CN is a way to determine the best subset of measurements to be paired with the manipulated variables. It is calculated by looking at the relationship between the maximum and the minimum singular value of the gain matrix (Seborg et al. 2011). By dividing the largest singular value by the smallest singular value, it is tested if the system is well conditioned. In the context of the optimal pairing of controlled variables with manipulated variables for the design of regulator control layer, a low condition number for a given pairing candidate indicates that the controlled variables can be regulated independently of each other. Thus based on the condition number of the individual subsets of measurements, the subset(s) best suited for further analysis can be chosen.

$$\text{CN} = \frac{\sigma_{max}(\boldsymbol{G}_{s,nxn})}{\sigma_{min}(\boldsymbol{G}_{s,nxn})} \qquad \text{eq. (9)}$$

where σ are the singular values of the transfer function gain matrix, $\boldsymbol{G}_{s,nxn}$, which is a square subset of $\boldsymbol{G}_s$ with the number of rows and columns equal to the number of manipulated variables.

The RGA is another method to find the best pairing between measurements and actuators. However, for a process with time delays, the process dynamics can be important in the pairing decisions. Considering this, the frequency-dependent RGA (f.d. RGA) is a better tool, where the calculation is based on the gain matrix instead of the steady-state gain matrix. The f.d. RGA can be calculated for a square matrix as follows (Bristol 1966):

$$\text{f.d. RGA} = \left(\boldsymbol{G}_s{}^T\right)^{-1} \otimes \boldsymbol{G}_s \qquad \text{eq. (10)}$$

For the pairing one should avoid negative relative gains and very large relative gains. A good pairing is indicated by a relative gain close to 1.

The calculation of the condition number showed that for this case study the interesting subsets of measurements are the same during the operational modes dry weather and emptying, and again they are very similar during filling and saturation (Paper II).

Based on the CN a subset for each of the operational modes was selected for further analysis with the f.d.RGA. The results of the f.d.RGA can be seen in Table 3.

Table 3: The f.d. RGA for the case study (Paper II).

	Dry weather			**Filling**			**Saturation**			**Emptying**		
	FM_{ES}	V_{KG}	FM_{SA}	FM_{ES}	IO_{KG}	FM_{SA}	FM_{ES}	IO_{KG}	FM_{SA}	FM_{ES}	V_{KG}	FM_{SA}
P1	1	0	0	1	0	0	1	0	0	1	0	0
P2	0	1	0	0	1	0	0	1	0	0	1	0
P3	0	0	1	0	0	1	0	0	1	0	0	1

The f.d. RGA shows that the control loops are not interacting with each other, since the off-diagonal elements are zero.

3.2.4 The pairing of manipulated and controlled variables

Based on the CN and the f.d. RGA the pairings are selected as shown in Table 5. For each of the operational modes a control degree of freedom (CDOF) analysis is performed.

During the saturation phase the whole sewer system is saturated included all three controllers, and the CDOF is therefore zero. Control loops 2 and 3 both empty offline basins (P2 and P3), and therefore cannot act on the system during dry weather, when the tanks are empty. During the filling of the system the interceptor pipes are full, causing the overflow to the offline basins in the first place, thus making any attempt to empty the basins futile. The CDOF for the dry weather and the Filling is therefore one, as also indicated in Table 4. Only during the emptying phase does the system have full CDOF.

Table 4: Results of the control degree of freedom analysis for each of the operational modes.

Operational mode	Control degrees of freedom
Dry weather	$\left.\frac{\partial CV}{\partial MV}\right\|_{Dry\ weather} \sim 1$
Filling	$\left.\frac{\partial CV}{\partial MV}\right\|_{Filling} \sim 1$
Saturation	$\left.\frac{\partial CV}{\partial MV}\right\|_{Saturation} \sim 0$
Emptying	$\left.\frac{\partial CV}{\partial MV}\right\|_{Emptying} \sim 3$

The CDOF analysis shows that the potential for control primarily lays in a quick emptying of the sewer system to avoid coupled event. However, to the extent that the downstream basin fills up before the upstream one, control loop 1 can be used to retain combined sewage in the upstream part of the system, and thereby ensure an even filling.

Based on the CDOF analysis, it can be concluded that not all operational modes are feasible for every control loop. In Table 5 some of the pairings are written in bold letters. These are the operational modes for each of the control loops, where the control loop is actually feasible.

Table 5: The pairing of MVs and CVs (Paper II).The operational modes written in bold are the feasible operational modes.

	Control loop 1 MV1 – CV1	**Control loop 2 MV2 – CV2**	**Control loop 3 MV3 – CV3**
Dry weather	$\mathbf{P1 - FM_{ES}}$	$P2 - V_{KG}$	$P3 - FM_{SA}$
Filling	$\mathbf{P1 - FM_{ES}}$	$P2 - IO_{KG}$	$P3 - FM_{SA}$
Saturation	$\mathbf{P1 - FM_{ES}}$	$P2 - IO_{KG}$	$P3 - FM_{SA}$
Emptying	$\mathbf{P1 - FM_{ES}}$	$\mathbf{P2 - V_{KG}}$	$\mathbf{P3 - FM_{SA}}$

As the pairing for control loop 2 becomes irrelevant for all operational modes besides emptying, this removes the problem of this control loop having changing pairings. For this case study, the pairings of MVs and CVs therefore remain the same during all relevant operational modes.

Though the CDOF is zero during the saturation phase, control loop 1 is still characterized as feasible. This is because in the implementation it will try to act on the system, however, the CDOF is zero and thus the controller is saturated; unless the controller is purposely deactivated during the saturation phase.

From the CDOF analysis it becomes clear that the regulatory control layer cannot have a fixed setpoint, as the dynamics are not continuous and have too large fluctuations for a single nominal setpoint to be sufficient.

3.2.5 Choice of control technique

Since the pairings are the same for all operational modes, the control techniques can also remain the same for all operational modes. By default the simplest control technique possible is selected for all three control loops: the proportional controller (P-controller) (Seborg et al. 2011):

$$u(t) = \bar{u} + K_c\big(y(t) - y_{SP}(t)\big) \qquad \text{eq. (11)}$$

where $\bar{u}$ is the nominal input, K_c is the controller gain, $y(t)$ is the measurement of the CV and $y_{SP}(t)$ is the setpoint.

Control loops 1 and 3 both have flows as both the controlled and the manipulated variable. Because of the transient nature of the disturbances, it is not possible to select a nominal input, $\bar{u}$, that leads to a stable P-controller for these loops. Instead an Integral-controller in velocity form is used, where the nominal input flow is replaced with the last recorded input value, u_{t-1}:

$$u(t) = u_{t-1} + K_c\big(y(t) - y_{SP}(t)\big) \qquad \text{eq. (12)}$$

Control loop 2 on the other hand, has a volume (V_{KG}) as the controlled variable. Here a standard P-controller is applied (Paper II).

For the determination of setpoints, the objective function for the control (eq. 1 and 2) is considered together with operational knowledge of the system. It is found that control loop 1 needs to have different setpoints during the different operational modes. Because the controlled variable is highly influenced by disturbances, it is necessary to vary the setpoint of the controller to ensure a stable operation. A higher control layer is therefore needed, to feed setpoints to the regulatory control layer.

3.2.6 Lessons learned from designing a regulatory control layer

Based on the results in this chapter, it is considered possible to apply classical control theory on sewer system control problems, if a piece-wise linear model of the sewer system can be obtained. The following should be highlighted:

- The preliminary screening of measurements not sensitive to changes in the manipulated variables is an effective tool, as it quickly eliminates the measurements that are irrelevant for control purposes.
- The controllability analysis proved a strong tool for analysing the sensitivity of the measurements from actuator changes and helps in the pairing of actuators and measurements.
- The CDOF analysis can help to gain systems understanding as the results create an overview of the available actuators in the different operational modes.
- In a sewer system the regulatory control layer cannot have a fixed setpoint. It needs to have setpoints fed; either from a coordinating control layer or from an optimisation.

The fact that the regulatory control layer needs varying setpoints to perform meaningfully in sewer systems, is consistent with the discussion in section 2.2 on the role of the coordinating control layer. It was argued that in practice the coordinating control layer is often embedded into the regulatory control layer. The reason for this is now obvious; it is because the regulatory control layer cannot function on its own.

A disadvantage of the controllability method is the many steps that need to be undertaken to achieve the gain matrix. In this study a detailed model of the system was available. However, to get from that model to the gain matrix model, multiple steps had to be performed to simplify the model, linearize it in different ways and finally convert it to a linear model in the frequency domain. The process is time consuming and, maybe more importantly, working in the frequency domain is unknown for professionals working with urban drainage modelling today, as the traditional methods for analysing the sewer system operation is in the time domain.

3.3 Designing a coordinating control layer

The coordinating control layer is the second layer in the control hierarchy (see Figure 2, page 11). One of the techniques often applied here is rule-based control, as it is an intuitive way of managing constraints, if they are not too complex. In HOFOR the rules are usually designed based on: 1) An analysis of bottlenecks, and 2) Simulations and trial and error. These are therefore the steps employed in this section, as illustrated in Figure 9.

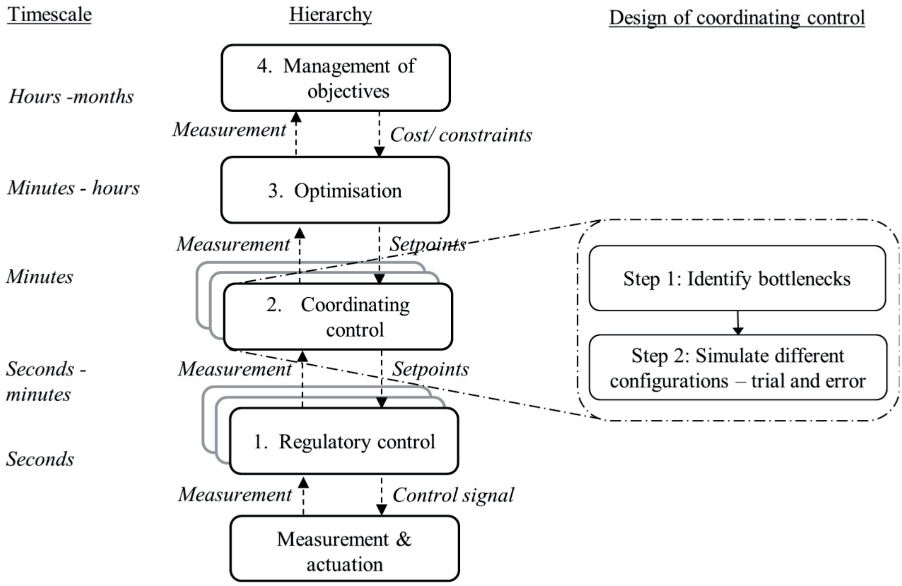

Figure 9: Steps in designing a coordinating control layer.

The steps are applied to the case study, and the results are described below.

From the review of the existing control system, it is known that there is a bottleneck downstream from P1, as P1 and P3 empty to the same interceptor pipe that has a limited capacity. During the emptying phase these two actuators therefore need coordination. It is chosen to prioritize the emptying of V_{SA}, and the setpoint for control loop 1 is therefore limited to 0.6 m^3/s, as this leaves enough capacity in the interceptor pipe for P3 to run at full capacity.

Based on the bottleneck analysis, and knowledge about the maximum capacity of the interceptor pipes and the dry weather flow, the setpoints and nominal flows of the controllers are chosen as shown in Table 6.

Table 6: The parameters of the three controllers when using coordinating control (Paper II).

Operational mode	Control loop 1			Control loop 2			Control loop 3		
	y_{sp} [m^3/s]	$\bar{u}$ [m^3/s]	K_c [-]	y_{sp} [m^3]	$\bar{u}$ [m^3/s]	K_c [-]	y_{sp} [m^3/s]	$\bar{u}$ [m^3/s]	K_c [-]
Dry weather	0.17	u_{t-1}	1	-	-	-	-	-	-
Filling	0.9	u_{t-1}	1	-	-	-	-	-	-
Saturation	0.9	u_{t-1}	1	-	-	-	-	-	-
Emptying	0.6	u_{t-1}	1	1440	0.5	0.2	1.0	u_{t-1}	1

Finally, a deadband is implemented in control loop 1 to avoid chattering, leading to frequent activation and deactivation of the controller during dry weather (Paper II).

The performance of the control system is tested with a CDS rain. The return period for the rain event is chosen to be two years[12], as this is still between the known return period for the overflows and the return period for surface flooding, but the system should not be so saturated that the control has no effect. The results of the simulation can be seen in Figure 10.

From Figure 10 it can be seen that the controller seems robust, and the configuration is therefore kept for the final evaluation as a potential new control system.

[12] The CDS rain is obtained from the Danish regional intensity-duration-frequency relationships (Arnbjerg-Nielsen *et al.* 2002; Madsen *et al.* 2009). The duration of the rain was set to four hours, the mean annual precipitation to 640 mm and the shape as symmetrical, resulting in a maximum intensity of 12.64 µm/s and a total rain depth of 23 mm.

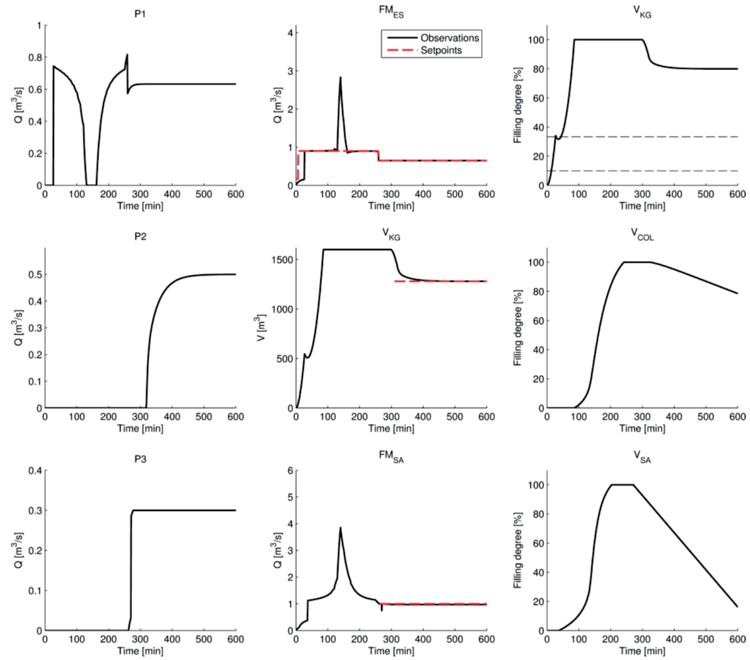

Figure 10: The results of a simulation with a CDS rain (T = 2 y) and a coordinating control layer acting on the regulatory control layer.

3.4 Designing an optimisation layer

An alternative to the coordinating control layer is to have the setpoints determined at an even higher layer in the control hierarchy. The optimisation layer is the third layer in the hierarchy. If an optimisation is implemented online, it can calculate and feed the optimum setpoints to the regulatory control layer automatically in a discrete manner (see Figure 2, page 11).

The optimisation problem can be generically formulated as follows:

$$\underset{\boldsymbol{u}}{\operatorname{argmin}} \int_{t}^{t+\Delta t} F(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d}) \qquad \text{eq. (13)}$$

subject to

$$\frac{d\boldsymbol{x}}{d\boldsymbol{t}} = h(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d}) \qquad \text{eq. (14)}$$

$$\boldsymbol{y} = g(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d}) \qquad \text{eq. (15)}$$

$$\boldsymbol{x}_{min} \leq \boldsymbol{x}_t \leq \boldsymbol{x}_{max} \qquad \text{eq. (16)}$$

$$\boldsymbol{u}_{min} \leq \boldsymbol{u}_t \leq \boldsymbol{u}_{max} \qquad \text{eq. (17)}$$

$$\boldsymbol{y}_{min} \leq \boldsymbol{y}_t \leq \boldsymbol{y}_{max} \qquad \text{eq. (18)}$$

where $F(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d})$ is the objective function for the optimisation, $h(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d})$ is the model of the system, $\boldsymbol{u}$ are the inputs or manipulated variables (MV), $\boldsymbol{x}$ are the states, t is time, Δt is the control horizon used, $\boldsymbol{d}$ are the disturbances and $\boldsymbol{y}$ are the model outputs or the controlled variables (CV). The indexes *min* and *max* indicate the lower and upper constraints.

In Figure 11 the different time horizons used in optimisation and the interrelationship between them are illustrated (from Rauch and Harremöes 1999). As indicated in Figure 11 the prediction horizon is the time it takes, before all effects have been accomplished. In a sewer system that is the retention time of the system, when focusing on CSO. The forecast horizon is the period where all the inputs are known. The control horizon is the simulation time of the optimisation and the sampling time is the time between recalculation of the optimisation and is denoted T_s.

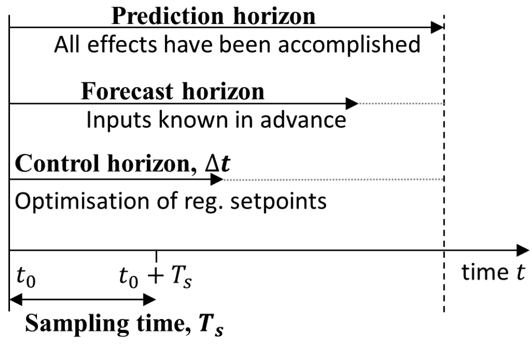

Figure 11: Schematics of time horizons applied in optimisation (from Rauch and Harremöes, 1999).

The methodology for designing the optimisation is taken from Seborg et al. (2011). However, as part of the design of the regulatory control layer, several of the steps have already been addressed. In this section the focus will therefore be on simplifying the process model, simplifying the objective function and performing a sensitivity analysis. The steps are illustrated in Figure 12.

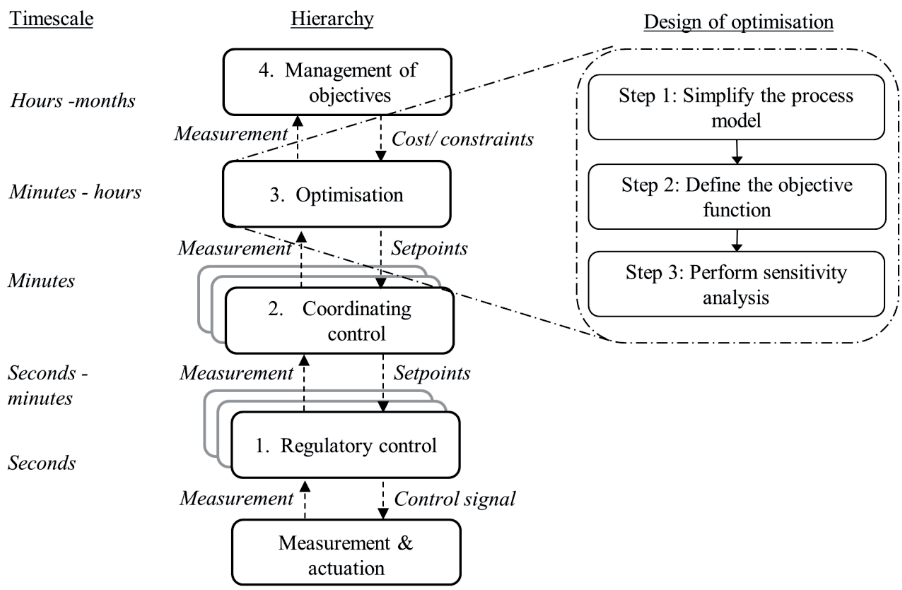

Figure 12: Steps in designing an optimisation.

The tools and methods of each of the steps were applied to the case study in Paper III. They are described in the following sections, as well as the results.

3.4.1 Simplify the process model

The VT model already described (section 3.2.1) can be used as both the evaluation model for benchmarking and the process model for the optimisation. However, the computational time of solving the optimisation is related to the model size and complexity. In this step the VT model is therefore simplified to different degrees and benchmarked against each other. The benchmarking parameters are chosen to be the root mean square error (RMSE) (Sin et al. 2007) and computational time.

$$\mathrm{RMSE} = \sqrt{\frac{1}{J}\sum_{j=1}^{J}\left(\hat{\boldsymbol{y}}_j - \boldsymbol{y}_j\right)^2} \qquad \text{eq. (19)}$$

where J is the number of observations, $\hat{y}_j$ are the simulation results of the process model and y_j are the simulation results of the evaluation model.

The model evaluation is performed with the CDS rain with a return period of two years also used in section 3.3.

Three alternative process models are tested and compared in Paper III to the full process model (VT model). Some characteristics of the models are shown in Table 7 (for the full descriptions please see Paper III).

The trajectories for the actuators are set from the evaluation model, since no control is yet applied. To make the performance of the model clear, no uncertainty is included in the simulations and the process model states are updated directly from the evaluation model. In any practical application the uncertainty and noise should be considered in the forecast and the model updating. However, these issues are kept outside the scope of this thesis.

Table 7: Optimisation model characteristics (Paper III).

Model	Modelling software	Process model equations	Estimated disturbances	Rainfall prediction	Forecast
1	Matlab	Algebraic	q3, q5, IC_{AH}*	No	Constant from measurements
2	Matlab/ Simulink	ODE	All	Yes	Mean of the previous period
3	Matlab/ Simulink	Algebraic	q1-q5, q7, IC_{OB}*	Yes	Actual future rain (perfect information)
VT	Matlab/ Simulink	ODE	All	Yes	Actual future rain (perfect information)

* See Figure 6, page 20.

The model dynamics are benchmarked against the evaluations model and each other with respect to the CVs (FM_{ES}, V_{KG} and FM_{SA}) using eq. 19; and the simulation times are also recorded[13]. The simulations are performed with a sampling time of both five and 30 minutes. The results are shown in Table 8.

Table 8: Comparison of potential process models to be used in the optimisation (Paper III).

	RMSE [-]		**Computational time [s]**	
Sampling time	5 min	30 min	5 min	30 min
Model 1	39.44	264.18	0.288	0.260
Model 2	10.88	55.12	14.762	5.610
Model 3	3.67	4.40	12.626	3.133
VT model	0	0	22.590	7.259

The results in Table 8 clearly show the choice one has to make, when choosing the model for optimisation. The slowest model is also the most detailed model (the VT model) and therefore has the best fit. All four models have

[13] The simulations are performed on a HP PC with Intel® Core™ i7-2600 CPU @ 3.40GHz in Matlab 2013a.

short computational times, since they are all very simple and the case area is small. However, the results show that:

- Going from a model implemented entirely in Matlab (Model 1), to the VT model implemented in Matlab/Simulink (Model 2, 3 and 4) has a significant effect on the computational time, simply because it takes time to repeatedly initialise and run an ODE model.
- The computational time can be kept down, while still maintaining an acceptable fit, if the rainfall prediction is done separately and then fed to the optimisation as an input as done in Model 3.
- With no rainfall forecast, a model with frequent sampling time will still perform reasonable. Even Model 1 with a two minute update has a RMSE of 13.08 and a computational time of 0.263 s.

For all subsequent analyses the VT model is used as both the process and the evaluation model as this is the option with the lowest RMSE and the computational time was affordable for the case study under consideration.

3.4.2 Define the objective function

The overall objective was defined in section 3.1 as minimizing the CSO volume. However, translating this to a mathematical problem to be solved by the optimisation can be done in different ways (Schütze *et al.* 2004b, Fiorelli *et al*. 2013). The following were investigated Paper III:

1) Minimising the CSO volume:

$$F_1 = \sum_{h=1}^{H} \sum_{j=1}^{J} \boldsymbol{UO}_{h,j} \qquad \text{eq. (20)}$$

where H is the number of external overflows, J is the number of observations and $\boldsymbol{UO}_{h,j}$ are the external overflow observations.

2) Using as much of the storage capacity as possible by ensuring an even filling degree:

$$F_2 = \sum_{k=1}^{K} \text{abs}\left(fd_{ev} - \frac{x_k}{x_{k,max}}\right) \qquad \text{eq. (21)}$$

where x_k is the volume of water in the basins, K is the number of basins, $x_{k,max}$ is the storage capacity and fd_{ev} is the even filling degree, which is calculated from:

$$fd_{ev} = \frac{\sum_{k=1}^{K} x_k}{\sum_{k=1}^{K} x_{k,max}} \qquad \text{eq. (22)}$$

3) Maximizing the flow to the treatment plant:

$$F_3 = \sum_{l=1}^{L} \text{abs}(y_l - y_{l,max}) \qquad \text{eq. (23)}$$

where y_l is the flow at the bottleneck, $y_{l,max}$ is the maximum capacity at the bottleneck and L is the number of bottlenecks in the system.

Each of the three objective function formulations was tested in Paper III using the CDS rain also previously used (section 3.3). The sampling time and the control horizon were selected to be 15 minutes, to account for the transportation lag-time in the system.

The results showed that:

- Formulating the objective function as a direct minimisation of the CSO, F_1, is not necessarily the best option. The problem with this objective function formulation is that it is only relevant when overflow is predicted or occurring.
- The alternative of using even filling degree, F_2, has the problem that when the majority of the tanks are full, there is nothing driving the emptying of the basins.
- F_3, where the focus is on maximising the amount of treated wastewater, performed well with respect to minimizing the CSO. However, an unwanted interaction between the actuators in control loops 1 and 2 occurred, resulting in fluctuations in the flow. This was due to an upstream-downstream causality caused by large differences in pump capacities and the size of the volumes.

The problems of F_3 were solved by using a multi-objective function:

$$F_4 = w_1 F_3 / F_{3,max} + w_2 (z - z_{SP}) / \Delta z_{max} \qquad \text{eq. (24)}$$

where w_1 and w_2 are weighting factors, z_{SP} is the desired volume in the tank to be kept, z is the actual volume and Δz_{max} is the maximum deviation possible from the desired setpoint.

In this fourth objective function formulation deviations from a predetermined water level in V_{KG} were penalised and added to the objective of maximising the amount of treated water. For the initial evaluation the weights of the two terms in the objective function were both kept at one. The results showed that introducing the second term in eq. 24 did not have a negative influence on the amount of CSO, but it did decouple the interacting loops to some degree (see Figure 13). From Figure 13 it can even be seen that imposing the penalty leads to a faster emptying of V_{COL}, which reduces the risk of overflow due to coupled rain events. Based on the results objective function four is chosen for further evaluation.

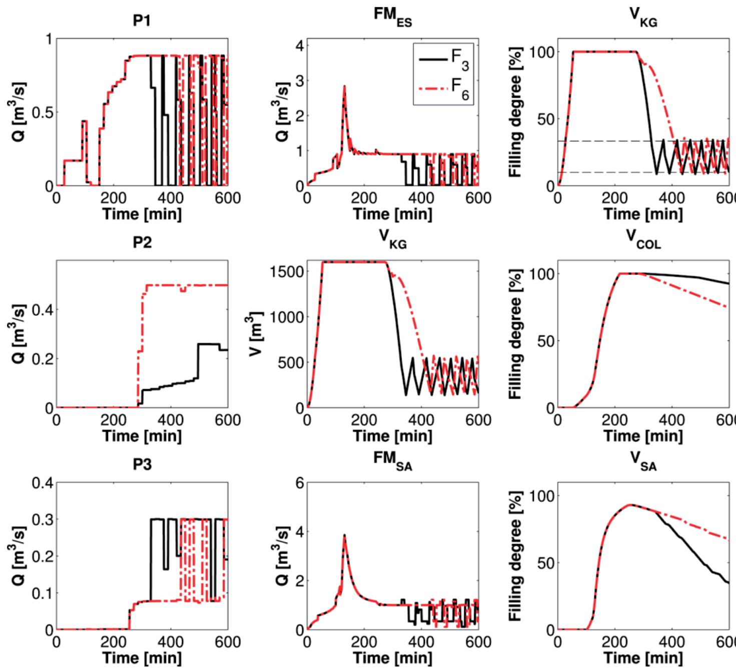

Figure 13: The simulation results with objective function three (F_3) and four (F_4). The first column shows the MVs, the second shows the CVs and the third shows the connected volumes.

3.4.3 Perform sensitivity analysis

If the optimisation model is ill-defined, this will of course be reflected in the optimisation results. Therefore a sensitivity analysis and tuning is performed, to identify if the optimisation problem and its solution can be further improved. A local sensitivity analyses is performed:

$$S_1 = \frac{\partial F}{\partial \theta_n} \qquad \text{eq. (25)}$$

where F is the objective function and θ_n are the parameters to be investigated.

Large values of S indicate that the objective function is sensitive to changes in the parameter. A negative value indicates a better performance, while a positive value indicates the opposite. The degrees of freedom investigated in Paper III are the weighting factors used in eq. 24 of the objective function formulation (w-values). The sensitivity analysis is performed with a historic, coupled rain event[14], to account for coupled events.

The objective function (eq. 24) contains two terms, with each their own weight. These weights are perturbed one by one with +/- 20 % and the sensitivity is calculated from eq. 24. As it was discussed in section 3.4.2 the first term minimizes the overflow, while the second term has the benefit of ensuring a quick emptying of the basins. This should minimise the risk of overflow from coupled events. In Table 9 the results of the sensitivity analysis are shown.

Table 9: Sensitivity analysis of the weights of the objective function (Paper III).

			w_1			
	UO17	UO32	UO38	UO42	UO44	Total CSO
- 20 %	0	-85	0	0	0	-85
+ 20 %	0	-100	0	0	0	-105
			w_2			
	UO17	UO32	UO38	UO42	UO44	Total CSO
- 20 %	0	-85	0	0	0	-85
+ 20 %	0	-20	0	0	0	-25

The results show that it is mainly the UO32 that is sensitive, and it is to changes in both weights**.** The negative sensitivities show that the total CSO

[14] From The Water Pollution Committee of The Society of Danish Engineers' (in Danish: Spildevandskomiteen (SVK)) rain gauge system, gauge 5740, event: 29-07-2005 to 30-07-2005.

discharge is less in all the scenarios than in the baseline scenario. In paper III addition effort was therefore put into determining the optimal value for w_1 and w_2. It was found that the relationship between the performance of the optimisation and the choice of weights is not one, where the global minimum is easily found. However, the weight of w_1 does not only affect the results in terms of the objective function, but also the stability of the output. In Figure 14 the results of the optimisation are plotted, with w_1 = [0.1; 1; 10] and w_2 kept constant at one. The results show that the output for the CVs becomes more stable, as the value of w_1 decreases, since this puts more emphasis on the second term of the objective function, which is designed to minimize fluctuations in V_{KG}. Based on the results of the sensitivity analysis the weights were chosen to be w_1 = 0.1 and w_2 = 1 for the final evaluation.

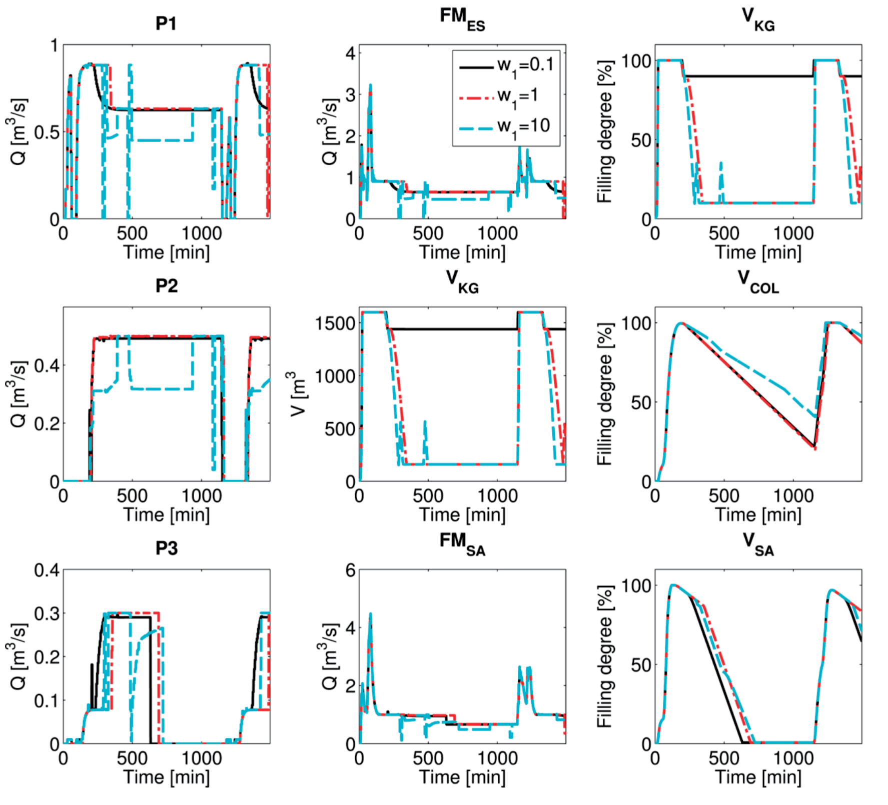

Figure 14: Simulation results from performing the optimisation with varying values of w_1 (0.1; 1; 10), while w_2 is kept constant (w_2 = 1).

Apart from the traditional sensitivity analysis, a tuning of the control horizon (Δt) together with the sampling time (T_s) is also performed. The two parameters are linked as shown in Figure 11, page 34.

The tuning is done from simulating a number of scenarios and comparing them based on the CSO volume (eq. 1 and 2).

In paper III a value below and a value above the 15 minutes used in the previous simulations, were selected for the control horizon. Five minutes was chosen, since this is less than the transportation lag-time in the system, and the effect of this is interesting to observe. For an upper bound, the problem was considered similar to that of tuning a controller. The approximated first order time constant of the system is 35 minutes and therefore 30 minutes was selected as the upper bound for the control horizon, since this ensures that the controller can act faster than the system dynamics. The sampling time was selected to be the same as the control horizon. As the sampling time cannot be larger than the control horizon, the scenarios to test were: $(T_s, \Delta t) \in$ [5,5 ; 5,15 ; 5,30 ; 15,15 ; 15,30 ; 30,30].

The scenarios were run with the CDS rain previously used (section 3.3) as well as a historical rain event with a similar return period[15]. The results of the simulations of the scenarios are shown in Figure 15.

The results in Figure 15 show that:

- A long control horizon will not improve the optimisation results in this case study. Instead the performance becomes worse as the control horizon increases.
- The performance deteriorates as the difference between the sampling time and the control horizon increases.

[15] From the Danish Wastewater Committee (SVK) rain gauge system, gauge 5740, period: 1979-2013, event: 22-05-2011. The return period is determined based on the maximum mean intensity over 30 minutes.

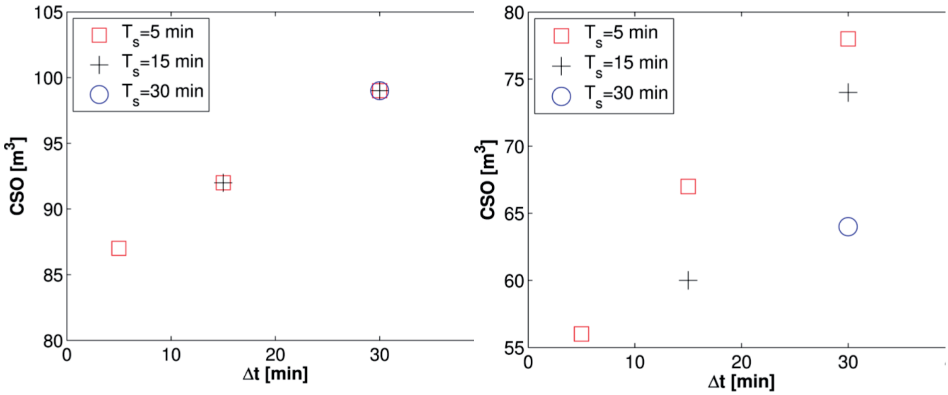

Figure 15: Results from sensitivity analysis of the control horizon, Δt, versus the sampling time, T_S. To the left are the results with the CDS rain as input. To the right are the results with the historic rain event as input (Paper III).

The reason the long control horizon will not improve the optimisation results is because the long control horizon has a dampening effect on the fluctuations in the optimum actuator outputs as the optimisation finds the average trajectories over the course of the horizon that yields the best results. However, as rainfall is quickly changing, an average trajectory may have too slow changes, to effectively reject disturbances. To account for this, a setpoint trajectory could be determined instead of a constant setpoint, as done by for example Pleau *et al*. (1996), Cembrano *et al*. (2004), Fiorelli *et al.* (2013), Courdent et al. (2015).

The results of the sensitivity analysis and the tuning are very case specific and can therefore not be generalized. They do however show the importance of performing such analyses, as it can have a significant effect on the results. Based on the results both the forecast horizon and the control horizon are chosen to be five minutes.

3.4.4 Testing the performance

Based on the results of the previous sections, the final configuration of the optimisation for the case study tries to minimise the CSO indirectly by maximising the flow out of the system, while limiting the fluctuations in the actuators:

$$\underset{\boldsymbol{u}}{\operatorname{argmin}} \int_t^{t+5\ \mathrm{min}} 0.1((FM_{ES} - IC_{ES})/IC_{ES} + (FM_{SA} - FM_{out})/FM_{out}) + \left((V_{KG} - V_{KG,max} \times 0.9)/V_{KG,max} \times 0.9\right) \quad \text{eq. (26)}$$

with a sampling time, T_s, of five minutes.

Before performing a long term evaluation, the configuration was tested with the CDS rain used in previous simulations (section 3.3). The optimisation can act directly on the actuators as illustrated in Figure 16, left or through the exchange of setpoints to the regulatory control layer as illustrated in Figure 16, right. Both configurations were simulated in Paper III and the results are shown in Figure 17 and Figure 18.

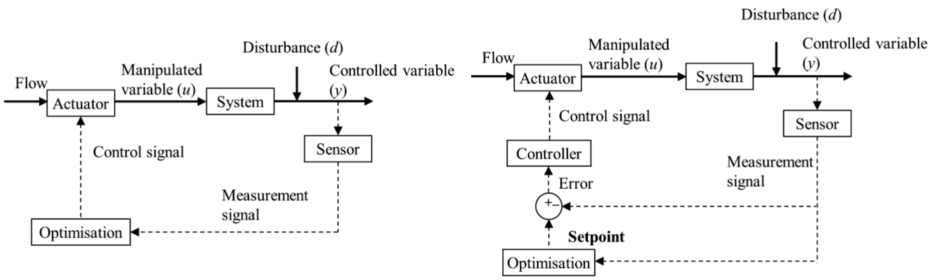

Figure 16: Block-diagram for optimising control (left) and feedback control with setpoints coming from an online optimisation (right) (Paper III).

From a comparison of the simulation results in Figure 17 and Figure 18 it can be seen that there is little difference in the performance of the control system, whether the optimisation acts directly on the actuators or through the exchange of setpoints. The results in Figure 18 show that the setpoints are largely followed; except for a short period of time approximately 120 minutes into the simulation. This is due to the saturation of the controller at the lower limitation; because the disturbances are so large, the controllers cannot fully reject them.

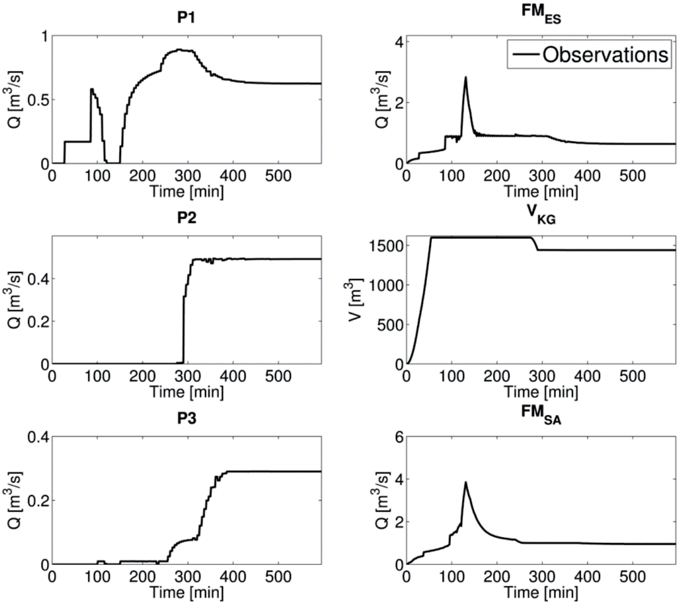

Figure 17: Simulation results when the optimisation is acting directly on the actuators (Paper III).

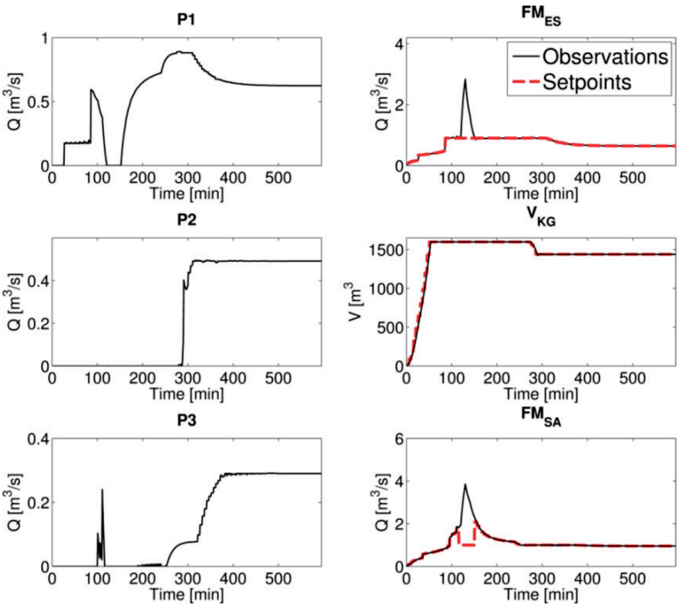

Figure 18: Simulation results when the optimisation is acting on the regulatory control layer (Paper III).

Traditionally the benefit of having the regulatory control layer is related to the reliability of the control system, as the regulatory control is embedded in local controllers, while the optimisation is performed at a remote server. Without the regulatory layer in place, the control system therefore becomes particularly vulnerable to communications failure. However, comparing the results in Figure 17 with the known bottlenecks of the system (Table 1, page 16), it can be seen that the setpoints for control loop 3 at times exceed the maximum capacity of the interceptor (the flow at FM_{SA} is above 1.0 m^3/s). For those control periods, setpoints above the capacity of the interceptor pipe may lead to the minimum overflow volume, despite the fact that it causes a downstream overflow. However, it cannot be considered a generally safe operating point. Therefore, it would be problematic if the communication failed at this point in time and no fall-back strategy was included in the regulatory control, as unnecessary overflows would then be the consequence. Therefore, in a sewer system the implementation of a regulatory control layer also needs the implementation of some type of fall-back strategy, similar to the designed coordinating control layer.

None the less, a benefit of the regulatory control layer is that for operators managing the sewer system, the presence of the regulatory control will provide an easy entry point for manual operation, in case of systems failure.

3.4.5 Lessons learned from designing an optimisation layer

Testing different models for the optimisation showed that the focus needs to be on both the computational time as well as the needed level of detail, which are contradictory requirements. There is no easy solution to this problem, but researchers are active in this field and different solutions are already implemented and being tested (e.g. Van Nooijen *et al.* 2011, Joseph-Durant *et al.* 2013, Vezzaro *et al.* 2013).

For the design of the objective function, it proved necessary to use a multi-objective, as none of the single objectives worked satisfactory for all operational modes. An alternative approach to the design of the objective function could be to have the objective function change according to the operational mode of the system. In this way the optimisation scheme becomes event driven. The advantage of this is that it allows for the optimisation objectives to change according to the state of the system, making it possible to manage multiple and often contradicting objectives. It of course entails the need for designing rules to switch between the different optimisation formulations;

these could be implemented as the “Management of objectives”-layer in the control system.

Testing the different objective function formulations showed that interaction is present between control loop 1 and 2, even though the f.d.RGA indicates that the control loops are independent (section 3.2.3). However, the correlation is only one-way, as it ties together with the upstream-downstream problematic, i.e. P1 can affect the CV of control loop 2, V_{KG}, while P2 cannot affect the CV of control loop 1, FM_{ES}. With systems with one-way interaction the RGA is always the identity matrix (Häggblom 1995). RGA should only be considered a guiding tool for the pairing; together with the CN. However, an alternative tool that should also take into account one-way interactions is the performance relative gain array (Shahmansoorian and Jamebozorg 2014):

$$\Gamma(s) \triangleq \bar{G}(s)G^{-1}(s) \qquad \text{eq. (27)}$$

where $\bar{G}$ (equal to diag$\{g_{ii}\}$) is the block diagonal system. The diagonal elements of the PRGA matrix are equal to the diagonal elements of the RGA. The PRGA should not give a different pairing, and should not have an effect on the results obtained here, but for future application it can possibly tell something about the interactions that the RGA cannot.

Finally the coupling between the optimisation and the regulatory control layer showed that in a sewer system the implementation of a regulatory control layer also needs the implementation of some type of fall-back strategy, similar to the previously designed coordinating control layer.

Apart from being more resilient to failure, an advantage of having the optimisation act on the regulatory control layer and not directly on the actuators, is that it provides an easy entry point for manual operation, in case of systems failure, which can be considered an advantage by operators.

3.5 Evaluation of control systems

Using the methods and tools of classical and modern control theory a methodological approach has been taken in the design of three novel control systems:

1) A regulatory control layer, with setpoints coming from a rule based coordinating control as described in section 3.3.

2) An optimisation layer where the optimization acts directly on the actuators, as described in section 3.4.4.
3) An optimisation acting on the regulatory control layer, as described in section 3.4.4.

These three control system alternatives are benchmarked against each other and the existing control, described in section 3.1. The benchmarking parameters are chosen to be the overflow volume at each of the overflow locations (eq. 1) as well as the total CSO volume (eq. 2).

For the benchmark evaluation a historical rain series of one year is simulated (2011[16]). The results can be seen in Table 10.

Table 10: Benchmarking results with respect to control system configurations.

	UO17 [m^3]	**UO32** [m^3]	**UO38** [m^3]	**UO42** [m^3]	**UO44** [m^3]	**Total CSO** [m^3]
Existing control	330	3,049	1,993	97	665	6,133
Regulatory control + coordinating control	328	3,282	654	95	626	4,986
Optimising control	331	3,508	912	102	668	5,520
Regulatory control + optimisation	331	3,466	876	107	674	5,455

The results of Table 10 show that all perform around 10-15 % better than the existing control. However, the regulatory control performs relatively better than both the optimising control as well as the hierarchical control system with setpoints coming from the optimisation. This can possibly be attributed to the following features of the system design and comparison:

- The tuning of the weights of the objective function. An emphasis had to be made on the stability of the controlled variable, at the expense of the term minimizing the CSO.

[16] SVK rain gauge 5740.

- Because of the simplifications made (no noise, evenly distributed rainfall, constant dry weather flow), the coordinating control layer could be designed to fit the system dynamics.
- The size and complexity of the case study is limited. This makes it possible to get the necessary overview of the sewer system dynamics and interactions needed to design the rules of the coordinating control properly using control theory (see Mollerup et al. 2015), which is instrumental for the success of the regulatory control layer.

The true potential of having optimisation arises, when a system has many control loops with limiting constraints and/or changing prioritisation between them (Larsson and Skogestad 2000). For a sewer system this can be due to the spatial distribution of the rainfall, changing operating conditions such as dry and wet weather or temporary system changes due to for example systems repair. But for small sewer systems with few actuators, a simple SISO control system is often enough (also called local control (Schütze *et al.* 2004b)). With a fine tuning of the weight the optimisation might still be able to perform slightly better or at least as well as the control system with the coordinating control. However, the results indicate that for small sewer systems, where the complexity is limited, it is not necessary needed to implement advanced optimisation based control systems to obtain a large improvement of the system. Therefore, it is also advisable to approach the design of a control system in a systematic manner, where the design and evaluation can be done step by step

3.6 Methodology for designing sewer system control

Based on the experiences with using both classical and modern control theory to design sewer system control in the earlier section, a methodology is proposed in Figure 19. The methodology matches the time-scale dependent control hierarchy presented in Figure 2 on page 11.

Apart from the steps included in this thesis, a review step is also included, where the need for (improved) control is evaluated. Though this step was not performed here, it should of course be conducted in practice before further steps are taken towards designing a control system. To evaluate the potential Schütze et al. (2004b) proposed the PASST guideline in 2004 that is effective for the preliminary screening (Dirckx *et al.* 2011). Another method could be data analysis of both historic data (if available) and simulation results, to analyse if all of the sewer system is saturated, when overflow occurs, or if sections of the sewer system are consistently partly empty.

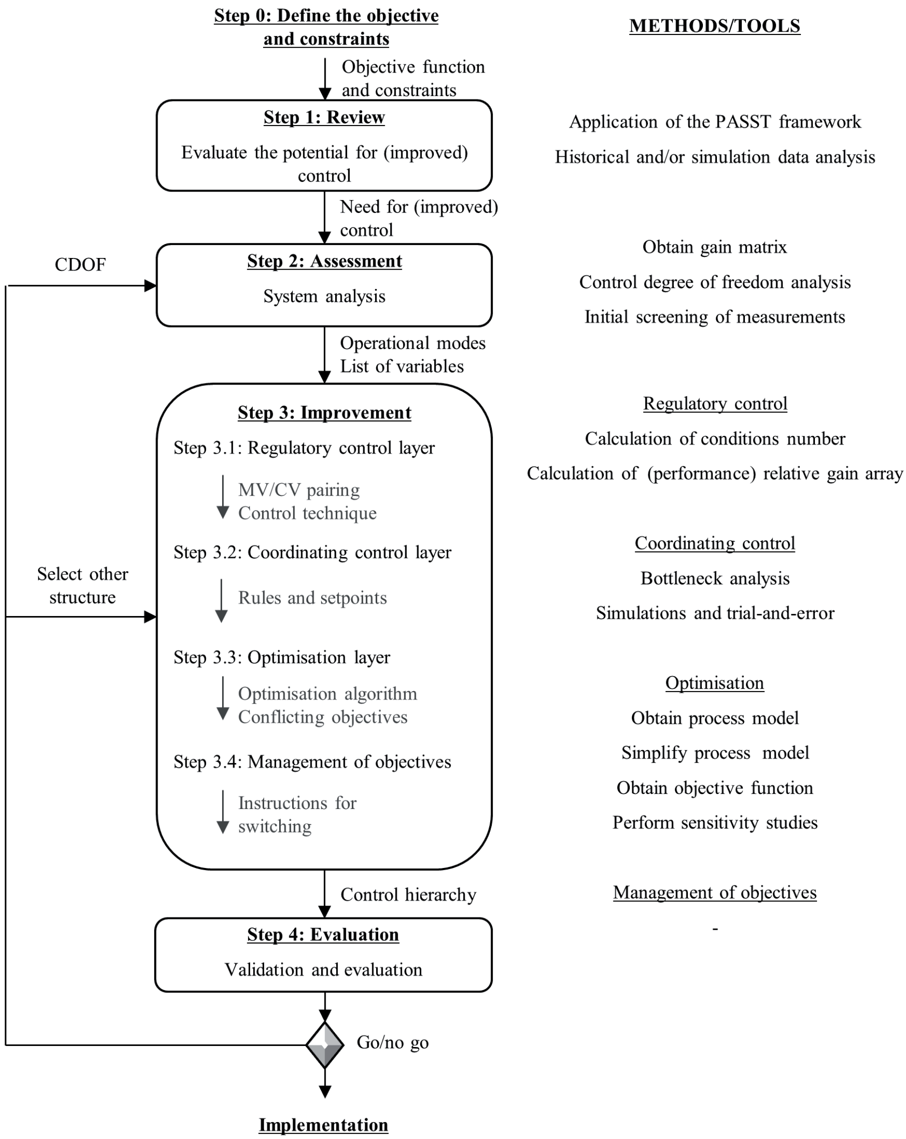

Figure 19: Methodology for designing sewer system control (extended from Paper III).

The second step, assessment, is the equivalent to the top-down analysis step in Larsson and Skogestad's (2000) design procedure. The output of this step is the operational modes and a list of variables (MVs, MeVs, and potential CVs). To obtain this output the CDOF analysis suggested in section 3.2.4 can be of help as well as obtaining the gain matrix and performing the initial screening of measurements.

Methods and tools for designing coordinating control layers have not been investigated in detail in this thesis. The methods and tools for coordinating control design are those applied in HOFOR today, when designing rule-based control. Other techniques are available that will require a different set of tools and methods.

As mentioned in section 2.2 there are no known implementations of the management of objectives layer. Therefore, there is no known experience in how to design it, and the tools and methods will need to be developed as the need arises.

To further strengthen the framework, methods and tools to manage uncertainties when designing the optimisation could be added. One of the big obstacles towards designing and implementing control hierarchies comes from not knowing how to effectively handle model, measurement and prediction uncertainties when implementing the optimisation (Breinholt et al. 2008).

4 Conclusions

In the first paper the two first research objectives were addressed. It was found that sewer system control can be decomposed with respect to time-scale, as done in traditional process control. Based on a review of existing sewer system controls a new time-scale dependent control hierarchy for sewer system control was therefore proposed. Also a terminology was proposed, which is extended in this thesis. By combining the time-scale dependent control hierarchy with the terminology, a framework is formed that can facilitate clear communication between different professions and disciplines working together in sewer system control design.

In the second paper the third and fourth research objective were addressed, and also the fifth was partly investigated. A stepwise approach to designing regulatory control of the sewer system was proposed that builds on classical control theory, and using a case study the methodology was tested. From the results it was found that to use the methods and tools from classical control theory on a sewer system, it is necessary to obtain a piece-wise linear model of the sewer system. This was done by linearizing at various points in time during the simulation of a rain event. The results of the linearization showed that the sewer system dynamics could be divided into four phases, each characterised by the operational mode; dry weather, filling, saturation or emptying. Having obtained a piece-wise linear model for each of the operational modes, the tools from classical control theory, such as the calculation of the condition number and the relative gain array, could be successfully applied to the sewer system.

In the second paper it was also found that a constant setpoint for the regulatory control layer is not sufficient in sewer system control, as the setpoints need to vary according to the operational modes; this can also explain why the regulatory control layer in actual applications in sewer systems often has a coordinating control layer embedded.

In the third paper the fifth research objective was examined in full. In this paper modern control theory was applied to design two optimisation based control structures; the first had the optimisation acting directly on the actuators and the second had the optimisation acting on the regulatory control layer. The two optimisation based control structures were evaluated from a one year simulation and the results showed that there was little difference in the performance. However, the optimisation based control structures were also compared to the existing control and the regulatory control with setpoints coming from the coordinating control layer, and here the latter showed the best performance. This was not unexpected, since the true potential of having optimisation arises, when a system has many control loops with limiting constraints and/or changing prioritisation between them. With a fine tuning of the weight the optimisation might still be able to perform slightly better or at least as well as the control system with the coordinating control. None the less, the results showed that for small sewer systems, where the complexity is limited, it is not necessarily the best option to implement advanced optimisation based control systems. Therefore it is also advisable to approach the design of a control system in a methodological manner, where the design and evaluation can be done step by step.

From the results in Paper II and III it can finally be concluded that it is possible to derive a methodological approach for design of sewer system control, based on classical and modern control theory. Taking a systematic approach to the design problem has aided in finding three novel control solutions for a case study in an efficient manner.

Based on the experiences gained from designing the sewer system control systems, a methodology for designing sewer system control is therefore proposed that combined the steps, tools and methods used throughout the thesis. The proposed methodology provides a basis for gathering experiences with sewer system control design and knowledge sharing; and will help generate control systems that are more robust, more structured, have a better performance and are easier to maintain.

5 Perspective

5.1 The implications of the thesis on related projects on control

Simultaneously to the work carried out in this PhD, other initiatives in HOFOR and BIOFOS are in progress that relates to this work. The most important are the projects called "*Environmentally efficient technology to integrated control between sewer system and wastewater treatment plant* [17] (METSAM) and *Operational model for early warning and control*[18] (OMOVAST). Each of these is outlined in this section, and the main findings/challenges in relation to this project are highlighted.

5.1.1 METSAM

METSAM was an innovation project that finished in 2014. The involved partners were Krüger A/S, BIOFOS and HOFOR, all of which were partners in the *Storm- and Wastewater Informatics* (SWI) project[19]. The SWI project was a large triple helix research project with the aim to deliver several components of an intelligent real-time decision support system, following a drop of water from the cloud, throughout the sewer–wastewater treatment system and into the receiving waters.

The aim of METSAM was to put some of the results from SWI into practice. The project implemented an intelligent real-time decision support system called DORA for the integrated control between parts of the Copenhagen sewer system and Lynetten WWTP, using model based prediction and optimisation.

The optimisation was performed with a two hour control horizon and a two minutes sampling time. The optimisation would minimize the risk related to discharges from the wastewater system (bypass and overflow). The rainfall

[17] In Danish: *MiljøEffektiv Teknologi til SAMstyring af afløbssystem og renseanlæg*

[18] In Danish: Operativ model til varsling og styring

[19] Swi.env.dtu.dk

forecast was based on weather radar information. The design of DORA was therefore very similar in its construction to the optimisation developed in section 3. It was designed to act of the existing control structure. However, it proved to be a challenge to translate the outputs of DORA into meaningful setpoints, since the existing controllers were not designed to facilitate the implementation of DORA in the best way. This gave rise to a discussion on how to implement DORA. Instead of translating the output from DORA into setpoints for the existing controllers, one option could be to remove the existing controllers completely, having DORA act directly on the actuators, but keeping the existing controllers as a fall-back strategy in case of communications failure. Another option was to redesign the controllers such that they were able to reject disturbances while facilitating the implementation of the DORA. Operators favour the first solution, as it leaves them with the possibility to deactivate the optimisation if necessary, and instead activate the old control system. However, this means that the controllers will maintain a very high level of complexity in their fall-back strategies that needs continuous maintenance and awareness from operators. In relation to this thesis, the results have shown that the existing type of fall-back strategy is indeed needed, but the question for HOFOR is how complex these should be. The problems of DORA shows how early involvement of the operators is important, since any design of the control system needs acceptance and ownership from the operators to become a success after implementation.

Another challenge was the selection of process variables to be included in the optimisation. No methods were applied. Instead they were chosen from systems knowledge and operator preferences. This later proved a limitation, since significant variables were not included. Having in this thesis established a method for screening of measurements; it could be interesting to perform a controllability analysis of the actuators and measurements in case area of METSAM, to see how the results match the existing pairings.

5.1.2 OMOVAST

OMOVAST is an innovation project run by Krüger A/S together with BIOFOS, HOFOR and DMI[20]. The ambition is to develop a sewer system and terrain model that can run close to real time, such that it can be used to predict surface flooding and be used as a tool for early warning.

To be able to react a sufficient time in advance to the threat of an extreme rain event, a rainfall forecast is needed that exceeds the emptying time of the sewer system. An important part of the project is therefore to gain experience with the use of numerical weather model output as input for the model simulations. The numerical weather model has a forecast horizon of 48 hours, which is around twice the retention time of the sewer system.

At the moment the output from OMOVAST is merely a flood warning and any changes to the operation of the sewer system is done manually by the operators. However, it is the perspective of OMOVAST that this should be done automatically, with perhaps a manual authorisation procedure. Based on the time dependent control hierarchy presented in Figure 2, the task of switching to another objective is managed by the top layer, Management of objectives. With a time scale of hours, this also matches the top layer. However, how to incorporate such a switching procedure into the existing control system still needs clarification.

5.2 Future work

The first outcome of the thesis is the time dependent control hierarchy presented in section 2.2. The hierarchy represents a new way of viewing sewer system control. It has the benefit of being more nuanced that other frameworks otherwise found in literature (e.g. Schütze *et al.* 2004a, Marinaki and Papageorgiou (2005), Brdys *et al.* (2008) and Ocampo-Martinez (2010)). A strength of the framework is that it takes its basis from real cases. However, to fully test its applicability it would be interesting to:

[20] The Danish Meteorological Institute.

- Apply it in detail to a sewer system with many control loops and several layers.
- Apply it to a sewer system with water quality based objectives, to investigate if this gives reason for further expansion of the hierarchy, or potentially a change in the time scales of the layers.
- Extend the hierarchy to the WWTP, to see the implications of this.

A second outcome is the methodology for sewer system control system design. The results are based on analyses of a case study that was kept simple in size and complexity. This was necessary as the thesis represents the first steps taken towards a methodological approach to sewer system control system design. However, to further test the methodology the following should be addressed:

- The methodology for designing sewer system control was applied to a small case study where there was no need to decompose the control system horizontally at the higher layers of the hierarchy, as the complexity was limited by the low numbers of manipulated variables. A natural next step would be to test the methodology on a larger case study, to investigate how this would affect the control design process.
- Due to the analysis being performed with homogeneously distributed rainfall together with the structures of the sewer system having similar time of concentrations, the operational modes could be identified in a system-wide manner. This helped to keep the methodology simple. However, for other cases they may be specific to the individual actuators. To further test this and investigate the potential implication of this, more case studies need to be analysed.
- The control problem was kept very simple, as measurement noise was omitted, the rainfall was assumed evenly distributed and the uncertainties on the rainfall forecast neglected. An interesting next step could therefore also be to repeat the design process without these simplifications, to investigate how this would affect the design process.
- The VT model cannot handle backwater effects and water levels in the pipes are not expressed, only flows. As most sensors in the sewer system are level meters, it creates a gap from the theoretical evaluation to the real implementation that cannot be bridged easily. For

practical application it should be investigated if a more suited model can be obtained.

- As mentioned in section 3.2.6, an obstacle for actual application of the controllability analysis in practice is that it is performed in the frequency domain. An alternative is to obtain the process gain matrix from time-domain models e.g. step-change response analysis (Seborg et al. 2011). The disadvantage of this is that it is a time consuming task, since it will require many simulations to determine the gain matrices. However, others have succeeded in coupling Mike Urban with Matlab (Courdent et al. 2015). This enables the use of Mike Urban as the evaluation model and Matlab for modelling the controllers and performing any analyses, making the possibility of staying in the time domain very attractive. It could therefore be interesting to repeat the design process using these modelling tools and staying in the time-domain.

- The design of the optimisation focused on minimising the overflow volume. However, as the operational cost of the control is related to the fluctuations in the manipulated variables, this could also have been included in the objective function formulation. Therefore the input variation should be included as a benchmark parameter in future work.

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Part two

Paper I: **A.L. Mollerup**, P.S. Mikkelsen, D. Thornberg and G. Sin, 2015. Control system for sewer systems - a review of existing design frameworks in EU cities and the presentation of a time-scale dependent framework. *Urban Water Journal*. In revision.

Paper II: **A.L. Mollerup**, P.S. Mikkelsen, D. Thornberg and G. Sin, 2015. Regulatory control analysis and design for sewer systems. *Environmental modelling and software*, 66, 153-166

Paper III: **A.L. Mollerup**, P.S. Mikkelsen and G. Sin, 2015. A methodological approach to the design of optimisation and control strategies for sewer systems. In preparation.

I

Control system for sewer systems - a review of existing design frameworks in EU cities and the presentation of a time-scale dependent framework

Ane Loft Mollerup, Peter Steen Mikkelsen, Dines Thornberg and Gürkan Sin

1 INTRODUCTION

Since the 1970s the potential of using control of sewer systems (or real time control, RTC) as it is often called within urban drainage (Schütze *et al.* 2002)) has been discussed (e.g. Beck 1976). The first state of the art assessment was done in 1989 (Schilling 1989) and already then it was evident that RTC can be used to increase the efficient use of the sewer system and thereby reduce the frequency and magnitude of combined sewer overflows (CSOs) with minimal capital investments.

Despite RTC being a subject for research in urban water management for more than two decades most sewer utilities have little or no RTC implemented (Schütze *et al.* 2004). And that is despite the fact that often little additional effort is needed to operate a sewer system with RTC, compared to a conventionally operated system (Beeneken *et al.* 2013).

The motivation for this paper is to support the implementation of RTC in sewer systems, in particular by focusing on the perspective of the utilities on the problems of RTC design.

It has recently been discussed by Mollerup *et al.* (2013) that one of the reasons for the limited number of sewer systems with implemented RTC, is the lack of a knowledge sharing on control system design. With an increasing number of competing control and optimisation techniques to choose from like rule based control (e.g. Benedetti 2009, Langeveld *et al.* 2013), fuzzy control (Seggelke *et al.* 2013), model predictive control (e.g. Cembrano *et al.* 2004, Fiorelli *et al.* 2013) and real time optimisation (e.g. Korte 2010, Dirckx *et al.* 2011), it has become a complex and time consuming task to identify and design the best control system for a particular sewer system. Also the complexity of the control problem is continuing to increase as the ambitions for the application of control expand. Particularly since the EU Water Framework Directive was put in force in 2000 the emphasis in research have been on integrated control of the sewer system together with the wastewater treatment plant (WWTP) and the receiving waters (Butler and Schütze 2005, Benedetti *et al.* 2009, Langeveld *et al.* 2103). Furthermore, with the extension of the system boundary, the urban water planners face some new challenges when designing the control system such as quality based objectives (Vanrolleghem *et al.* 2005) and long time-constants (Harremoës and Rauch 1999). In this paper the control systems implemented in the sewer systems of three EU cities, Copenhagen (Denmark), Hoeksche Waard (the Netherlands) and Barcelona (Spain), are reviewed. Based on the review, the existing frameworks for control system design are discussed. Based on this a generic framework for decomposing sewer system control in a hierarchical manner based on time-scale is presented.

2 REVIEW OF IMPLEMENTED CONTROL SYSTEMS IN THREE EU CITIES

Control is the adjustment of available degrees of freedom to assist in achieving acceptable operation of the system (Larsson and Skogestad 2000). In a sewer system that means finding out how to operate the actuators such that the setpoints of the controllers are met and disturbances to the system are rejected.

If a single optimizing controller can be found that both stabilises the system processes as well as perfectly coordinate all the manipulated variables this is called centralised control (Larsson and Skogestad 2000). In theory, it should be possible to obtain a stable and optimal operation with a centralised control system. However, for large systems it is often not possible to design such a controller. Instead the control is decomposed in “blocks” either in a vertical way (hierarchical) or a horizontal way (decentralised or distributed control) (Larsson and Skogestad 2000).

The control structure is the structure that connects the controlled, manipulated and measured variables through the control and optimisation techniques and the control system is the entire architecture of the control (Larsson and Skogestad 2000).

The goal of the wastewater utilities is to achieve a control system that can optimise the performance with respect to the defined objectives such as minimizing the CSO volume, while keeping the operation stable.

The typical control structure in sewer systems is one where the control is decomposed in a horizontal way, meaning the control is distributed spatially to local controllers like PID or on/off controllers. This type of control structure can be very effective with respect to meeting local objectives, and it is still this type of control structure that is implemented in most sewer systems (Schütze *et al.* 2004).

However, in the last decades focus in research of sewer system control has been on designing control system, where the objective of the control is defined in a system-wide manner (Beeneken *et al.* 2013, Langeveld *et al.* 2013, *Fiorelli et al.* 2013), which points towards a hierarchical control system; and these types of control systems are also starting to get implemented around Europe.

In the preparation of this paper three wastewater utilities were visited with the objective of documenting the principles of their control system; Copenhagen in Denmark, Hoeksche Waard in the Netherlands and Barcelona in Spain. The reason for selecting these three cities was that the utility companies in all three cities have implemented or are investigating the use of higher layer control or optimisation techniques in the sewer system control. Some key characteristics for the three cities' sewer systems are compared in Table 1.

Table 1: Key characteristics for the three sewer systems

	Catchment area [ha]	No. Of WWTPs	No of CSOs	No of actuators	Relative capacity [mm]
Copenhagen	7,500	2	71	80	3.5
Hoeksche Waard	80	1	14	11	5
Barcelona	12,750	2	31	73	5

As it can be seen from the key characteristics in Table 1, the sewer systems in Barcelona and Copenhagen are both large systems with a similar amount of actuators available for control, whereas the sewer system in Hoeksche Waard is much smaller.

A survey was completed together with the utilities (one on one interviews) to gather information about the control systems. Based on this information the control systems are described and compared below.

2.1.1 Sewer system of Copenhagen, Denmark

The catchment of Copenhagen is mainly urban areas with high density, but it also covers less dense suburbs. The catchment is very flat and thus many of the actuators in the system are pumping stations with the primary objective to lift the water, so it can run towards the WWTPs by gravitation. Therefore in the beginning, the sewer system had only simple regulatory control (on/off and PID).

However, in the 1990's the utility company operating the sewer system in Copenhagen decided to implement more advanced RTC in the western part of the system. The goal of using RTC was to ensure a better utilization of large pipe volumes in the catchment.

The basis of the control was state-dependent rule based switching between dry weather, wet weather and emptying operation of the system (Andersen *et al.* 1997).

Today, many of the pumps and gates still have only regulatory control with on/off control, but more and more often on/off controllers are replaced with rule based controllers, where the rules are designed based on model simulations and operator experiences. A conceptual illustration of the Copenhagen sewer system control system is illustrated in Figure 1.

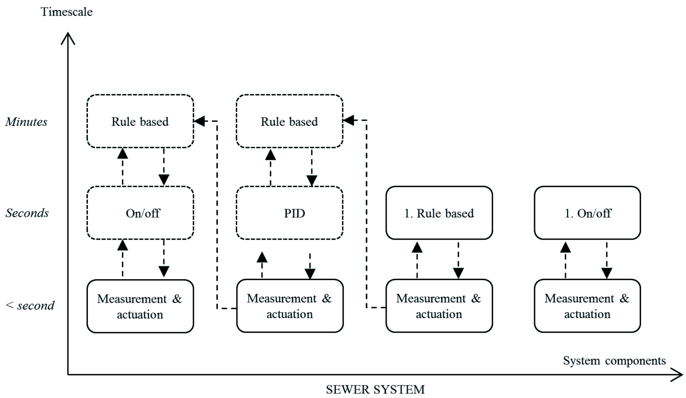


Figure 1: The control system in Copenhagen's sewer system.

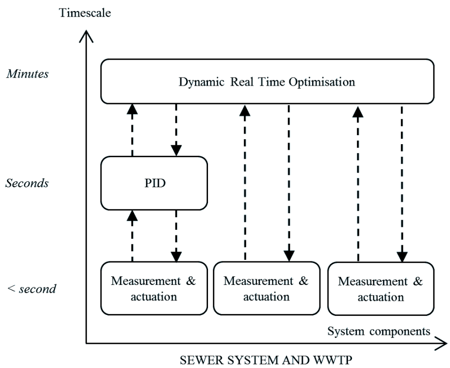
As it can be seen from Figure 1, the existing control system is a distributed one. Coordination between control loops is done by having a static prioritization between any fighting actuators. This prioritization is enforced through rules that are programmed into the local controller, allowing for a switching strategy for selecting the optimum setpoint for the controller.

The question for the utility companies in Copenhagen[1] is whether advances in the integration between the sewer system and the WWTPs can be made while continuing the use of rule based control. It is thought that the level of complexity is already too high. Further expansion of the

[1] The WWTPs and the sewer system in Copenhagen are owned and operated by different utility companies.

objective of the control system would only increase the complexity further. Therefore the utility companies operating the sewer system and the WWTPs are currently looking at other techniques to optimise the operation and coordinate the actuators of the sewer system, while respecting the load constraints of the WWTP.

At present a pilot project called *Environmental-efficient technology for integrated control of sewer system and WWTP*[2] is running in two of the WWTP catchments of Copenhagen. In this project a two hour forecast is used to predict the future state of the system and based on this the risk of overflow and bypass from the individual overflow structures is calculated. Using a genetic algorithm, an optimisation problem is solved, where the optimum flows of the controlled variables in the system are found (Grum *et al.* 2011). Actuators with an internal mapping between frequency or position and the flow (like pumps) can use the output of the optimisation directly as a control input signal, and hence there is no need for a regulatory control layer. Actuators without such an internal mapping will however need to have a regulatory layer to translate the setpoint of the optimisation into a control signal. A conceptual illustration of such as control system is depicted in Figure 2.



[2] The original title in Danish is: *MiljøEffektiv Teknologi til SAMstyring af afløbssystem og renseanlæg* (METSAM)

Figure 2: Possible future control system for Copenhagen's sewer system and WWTP.

From Figure 2 it can be seen that METSAM is currently developing an optimisation technique. The optimisation is expected to recalculate the optimum setpoints and actuator positions every two minutes. It is not yet clear if the optimisation is to cover the whole sewer system of Copenhagen or if the sewer system will be divided into subsystems that can be optimised individually.

Based on Figure 2 a concern can be the resilience of the control system. Since the optimisation will sometimes act directly on the actuators without an intermediate regulatory control layer, the robustness in case the optimisation layer fails for some reason, is low. Therefore it is also being discussed what fall-back controls there should be at the level of the regulatory layer.

2.1.2 Sewer system of Hoeksche Waard, Netherlands

The catchment of Hoeksche Waard covers mainly small cities and rural areas. Originally the sewer system had only simple regulatory on/off control and there was no integration between the WWTP and the sewer system. However, in 2009 water authority Hollandse Delta operating the WWTPs joined forces with the municipalities operating the sewer systems, to implement Real Time optimisation (RTO). The objective of the RTO is to distribute the wastewater evenly over the retention volumes in the sewer system, while meeting the hydraulic load at the WWTP. The result is a minimization of CSOs and no overloading of the WWTP (Van Nooijen *et al.*, 2011). The control system is illustrated in Figure 3.

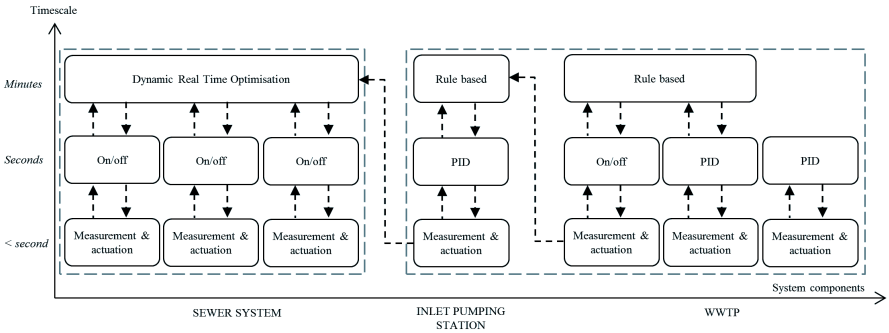


Figure 3: Control system for the wastewater system in Hoeksche Waard, Netherlands. The dotted boxes show the organisational boundaries.

As it can be seen in Figure 3, the integrated control of the WWTP and the sewer system comes from the use of measurements across system boundaries. Since the RTO only acts on the sewer system, the WWTP and inlet pumping station are still controlled autonomously.

The output from the RTO is on/off signals for the manipulated variables in the sewer system. These are sent to the start/stop controllers at the regulatory layer. Here the on/off signal is translated into a set of boundary values that force/allow the pumps to either start or stop.

The exchange of information between the local on/off controllers and the RTO is done every minute. This is necessary because the on/off controllers cannot reject disturbances effectively and with the small volume in the sewer system relative to the pumping capacity, the states change rapidly (Nooijen and Kolechkina, 2013).

2.1.3 Sewer system of Barcelona, Spain

The catchment of Barcelona is mainly dense city areas. The system has large pipe gradients in the upstream part that transports wastewater from the mountains in the west towards the lower laying beaches. As a result they often experience problems with flooding of the lower parts of the city and the control therefore has as a primary objective to minimize flooding by retaining water in the upstream retention basins.

The implementation efforts for RTC in the Barcelona sewer system began in 1996, and the control structure implemented in Barcelona today resembles the type of control structure currently implemented in Copenhagen. The large stations are mainly rule based, where the rules are designed from model simulations and operator experiences. However, the utility company responsible for the operation of the sewer system in Barcelona, Clavegueram de Barcelona S.A. (CLABSA) is also considering the implementation of a new control structure. It considers replacing the rule based control with MPC at the coordinating control layer, to improve the operation.

The challenge when using MPC is that it needs a model (usually a linear ODE type) that can describe the relationship between the manipulated variables and the controlled variables and is quickly solved, to keep within the timescale of the control hierarchy. Also the desired setpoints for the controlled variables have to be known.

The advantage is that MPC takes into account not only the present state of the system, but also the future state of the system by including a forecast of the inflow to the system. For a system like that of Barcelona, with large basins in the upstream part of the system and large transient flows due to the steep slopes of the pipes, the use of forecast seems particularly advantageous, since with MPC the controller should be able to keep abreast with the problem.

In Barcelona the model proposed for the MPC is a simple model of the sewer system, which is based on the conservation of the mass balance (Puig *et al.* 2009). The objective of the control system is to minimize both flooding and overflow. Therefore the controlled variables are chosen to be overflows and surface flooding flows. As both should be avoided, the setpoints for these controlled variables are zero at all times, and therefore there is no need for an upper layer feeding setpoints to the MPC.

In a sewer system the active constraints are mainly on the capacity of the actuators, as constraints on levels and flows could lead to setpoints that are impossible to obtain with the actuators of the system. Therefore the outflows from the actuators are chosen as the manipulated variables.

The output from MPC would be the optimum outflow values, i.e. the setpoint values for the manipulated variables. However for the gates, these are to be translated into valve positions that can be sent directly to the actuators. This means that the MPC will act directly on the actuators with no regulatory layer in-between. This makes the system very sensitive to communication failure and for this reason fall-back controls are implemented in the local PLCs that can take over, in case of missing signals from the MPC controller.

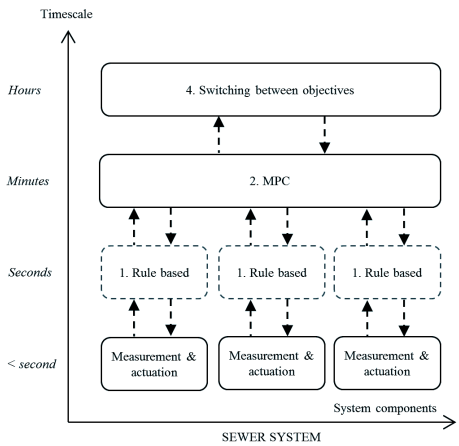


Figure 4: Control system with MPC as coordinating controller. The dotted lines to the rule based control techniques that the MPC does not act on these, but instead the rule based control techniques are only used in case of communication failure.

The control hierarchy aimed at in Barcelona is depicted in Figure 4, which shows a new type of layer in the control system that enables them to switch between objectives. From simulations CLABSA has found that their two primary objectives, avoiding flooding and minimising CSOs, work against each other and it has not been possible to tune the weighting of these to have a dynamic prioritisation. Avoiding flooding will always be the dominant term in the objective function. As a result they have included the management of objectives layer, which enables them to switch between the two objectives depending on the forecasted rainfall.

Though the control is not expected to be used in an integrated way with the WWTPs, the implementation of MPC opens up the possibility to easily add the inflow to the WWTP as a constraint or even as part of the objective function.

The MPC will cover the entire catchment and at the moment CLABSA, is preparing the control system for the implementation of the higher layer.

3 DISCUSSION AND PROPOSAL OF NEW TIME-SCALE DEPENDENT FRAMEWORK FOR SEWER SYSTEM CONTROL DECOMPOSITION

3.1 Comparison of the control systems and existing frameworks for control decomposition

From the review it was found that all three cities have an existing control system with a decentralised structure, where the control is distributed spatially to local controllers like PID or on/off controllers. In some places the controllers also feature rule-based switching between setpoints. However, the utilities in all three cities believe they can optimise the operation of the system by replacing the existing control system with a new one, where the objective of the control is defined in a system-wide manner.

The new control systems are best illustrated by hierarchies, where the setpoints for the local controllers are determined at a higher layer in the hierarchy.

The objective of the control system was basically the same in all three cities. They focus on minimizing CSO, but in Barcelona they also focus on flooding, which gave cause to an additional layer in the hierarchy compared to the two other cities.

Comparing the control hierarchies for the sewer systems in the three cities, it can be seen that the control systems being designed, are different with respect to the control structure as well as the choice of control and optimisation techniques. However, despite the three cases being different in many ways, the timescales are similar in all three cases, with the updating of setpoints for the regulatory layer/actuator signals for the actuators being recalculated every couple of minutes. This was somewhat surprising, since the systems are very different in size, and thus the time constants in the respective systems are expected to be very different. The reason they none the less are so similar could be that the timescale is not depending on the size of the system, but is related to the transient nature of the disturbances. With fast changing state variables, the optimum states and thus the optimum setpoints also need frequent updating.

The idea of decomposing the sewer system control in a hierarchical way was first proposed by Schütze *et al*. in 2004. They proposed a framework and introduced a terminology for control of the integrated wastewater system composed of sewers, WWTPs and receiving waters (Figure 1). The framework includes the terms management level, system level and field level.

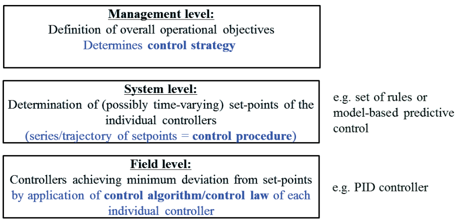


Figure 5: Decomposition of the integrated wastewater system control as proposed by Schütze *et al.* (2004).

At the field level the controllers try to achieve minimum deviation from the desired setpoints. At the management level the control strategy is implemented that defines and coordinates the overall operational objectives of the control, e.g. avoidance of discharge of suspended solids into the effluent, protecting river water quality, minimise electricity consumption, etc.

At the system level those desired setpoints are determined by the control procedure (using the terminology defined in this paper this is the control or optimisation technique) and on the field level a control law is applied for the individual controllers that enable the controlled system to achieve minimum deviation from the defined setpoint (Schütze *et al*. 2004).

Similar control hierarchies have been proposed by Marinaki and Papageorgiou (2005), Brdys *et al* (2008) and Ocampo-Martinez (2010). These studies did not explicitly specify the principle for decomposition, however we infer from the terminology used that the higher layers of the hierarchy are centralised and acting on the lower layer(s), which is decentralised.

Earlier proposed hierarchical decomposition frameworks focus primarily on the exchange of signals and not how these signals are obtained or how often they are exchanged. However, a hierarchical decomposition of the control is only possible if the higher layers operate at larger timescales than the lower layers they affect (Larsson and Skogestad 2000). A very important factor in the design of the control system is therefore to determine how often the exchange of information between the layers should be made; in other words how often the actions defined for a layer should be executed. An extended more comprehensive framework for design of sewer system control is therefore proposed with explicit communication and information flow as well as purpose of the layer. The proposed framework is made compatible with the control hierarchy known from plant-wide control of WWTPs (Olsson an Newell 1999). When moving towards integrated control between sewer systems and WWTPs it is considered a benefit for the field of urban water management, if the hierarchy could be extended to the sewer system control. However, wastewater treatment plants operate with continuous processes, which the sewer system does not. Since the sewer system dynamics are not continuous, but transient in nature, the framework cannot be directly transferred, but needs to be adapted.

3.2 Time-scale dependent framework for sewer system control decomposition

Here a hierarchy decomposing the control problem based on time-scale is proposed. However, as the ambitions and organisational boundaries for the use of control grows, decomposing the control with respect to only timescale might become too restricting. Therefore it should be kept in mind that decomposition based on differences in timescale is only one method for decomposition. Other methods such as spatial decomposition exist. Often the two methods are even combined, which is illustrated by the grey boxes at each layer in the hierarchy.

The proposed control system hierarchy is illustrated in Figure 6.

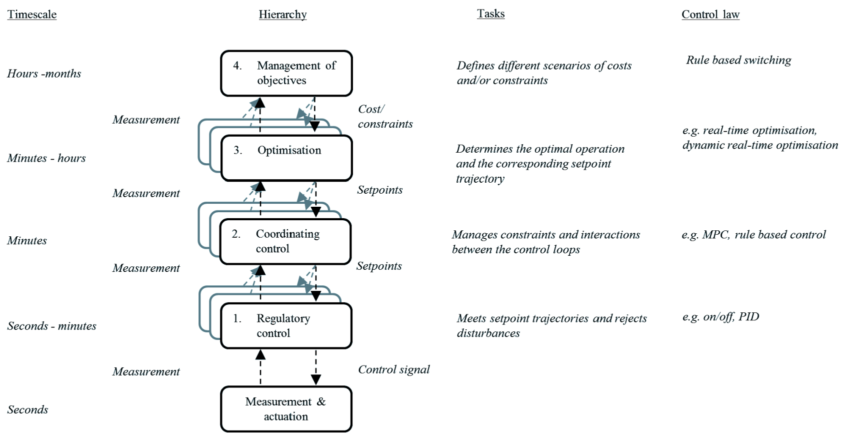


Figure 6: Hierarchical control structure for a sewer system with timescale decomposition. From the left: the first column shows the timescales, the second column shows the layers in the control hierarchy, the third column shows the tasks performed in these layers and the fourth column shows examples of control techniques used. The output and input information to each layer is also presented.

The two higher layers (management of objectives and optimisation) can be categorised as the management layers while the two lower layers (coordinating and regulatory control) can be categorised as the control layers.

The management layers ensure an economic operation of the system and determine the optimal operating point while the control layers drive the system towards the desired setpoints and once there reject dynamic disturbances (Rawling *et al.* 2012) such as changing rainfall runoff. The layers are linked by information passed between the higher and the lower layers (Larsson and Skogestad 2000).

Layer 4: At the very top of the hierarchy is the *management of objectives* layer, which defines the overall scope and targets for the sewer system operation that may take into account legislative requirements as well as operational objectives. Here constraints and costs used for the objective function in the optimisation are specified. Changes to the constraints and costs could be due to seasonal changes such as being in or out of the bathing season or a diurnal pattern of changing cost of electricity. Though no known control system for a sewer system have implemented a structure with such a layer today, it is included in the hierarchy as it naturally complements the control hierarchy and may become relevant in a near future, as in the case with Barcelona.

Layer 3: The task of the *optimisation layer* is to determine the optimum operation and the desired setpoints or setpoint trajectories for the control layers. This can be done online or offline, but in a sewer system the states change frequently and rapidly during a rain event. Therefore a setpoint will only be optimal for a short period of time. As a result the setpoint will have to be updated very often or instead of a single value, the optimisation could provide a trajectory of setpoints.

Layer 2: Below the optimisation layer there can be a coordinating control layer. The *coordinating control* layer is needed if the control loops are interacting or there are some constraints on either the manipulated or the controlled variables that cannot be violated. In a sewer system the primary constraints are often on the capacity of the actuators, but they could also be on the flow or water levels at key locations in the sewer system. The role of the coordinating control layer is to decouple interacting control loops and manage constraints.

Layer 1: The lowest layer controller is the regulatory control layer. The *regulatory control* layer ensures that the setpoints or trajectories are followed and that the disturbances are rejected.

What separates this framework from those previously proposed is the focus on the frequency with which the calculations are updated and information is exchanged between the layers of the hierarchy. In Figure 6 a suggestion for a timescale is made. The frequencies of action at the individual layers are specified as ranges, since these can be different for different sewer systems, depending on the number of layers and how fast the transients and responses of the system are. Since each layer acts at different timescales, the actions at the higher layers are discrete. This means that the system will never be able to achieve a truly optimal operation, since that would acquire a continuous determination of the optimum setpoints (Larsson and Skogestad 2000). As the determination of the timescales is important for a steady state system, it seems reasonable to extrapolate that this will be especially true for a system with a transient nature like that of the sewer system. The implication is that the choice of timescale becomes a balancing act between practical and computational feasibility, and approaching optimal behaviour through frequent updating and the use of more optimal, but also more time consuming techniques.

Ocampo-Martinez and Puig (2009) found that depending on the size of the control problem, i.e. the number of actuators, measurements and constraints, and the type of model used, the time it takes to converge to an optimal solution (i.e. computational time) may be too long for model based control techniques to be applicable in practice. The same claim is made by Schütze *et al.* (2004).

In relation to the hierarchical decomposition, this means that the techniques used at the higher layers must be able to solve the problem within a certain frequency for the control system to work.

The only frequency that is easily determined is that of the regulatory layer, since this has to be as close to continuous operation as possible, as fast reaction is needed at this lowest layer of the hierarchy.

The updating frequency for the coordinating control layer is based on the literature, where this is usually found to be around 5 to 10 minutes (Gelormino 1994, Pleau *et al.* 2005, Ocampo-Martinez and Puig 2009, Fiorelli *et al.* 2013).

The few documented implementations of optimisation layers in sewer systems points towards this layer having a similar updating frequency as the coordinating control layer (Van Noiijen *et al.* 2011, Grum *et al.* 2011). However, in these cases the control structures have no coordinating control layers. Instead the optimisation layer acts directly on the regulatory control layer. It is therefore inferred that the updating frequency for the optimisation layer will probably be in the range of minutes to hours.

The updating frequency for the layer of managing the objectives is related to the tasks this layer is expected to handle. In Barcelona the frequency was linked to the rainfall, but the frequency could also be linked to a seasonal pattern, such as being in or out of bathing season, or the diurnal patterns in the cost of electricity. Therefore the frequency is suggested to be between hours and months.

4 CONCLUDING REMARKS

The value of the time-scale dependent framework lays in its ability to visualise control structures in a manner that enables a comparison between them. This can be of value in the design phase, but will also continue to be of value in the proceeding development of the system. Having the control structure documented will enable the utility company to not only compare the system with others, but also help them in the maintenance and further development of the control system, which is an important aspect that is often neglected after implementation. By applying the framework in detail, an inventory is provided of the control loops, the control techniques used in the control system and at which layer in the hierarchy they are applied. This is helpful when pinpointing if and where updates are needed and where to begin when evaluating the control system.

Considering the hierarchy of the three case studies as well as case studies reported in open literature (Mollerup *et al.* 2013), it becomes obvious that much research today on control of the sewer system is focused on model-based optimisation techniques. Methods like those investigated by Puig *et al.*. (2009), Grum *et al.* (2011) and Dirckx *et al.* (2011) to name a few, are all to be used at the higher layers in the control hierarchy. The advantage of these types of techniques is the dynamic determination of setpoints for the actuators according to the actual state of the system. However, as these types of techniques are used at the higher layers of the hierarchy, experiences from other fields suggest that they should preferably act on lower layer controllers through the exchange of setpoints, to keep a high resilience. Therefore it becomes imperative that the higher layers are designed by considering (and not excluding) the rest of the hierarchy concurrently.

AKNOWLEDGEMENT

Thank you to Gustavo Wilhelmi and Xavier Sancho from the utility company CLABSA in Barcelona, Spain, and Edwin van Velzen from water authority Hollandse Delta in Delft, the Netherlands, for their hospitality and exchange of knowledge about their control systems.

Also thank you to Klaas-Jan van Heeringen from Deltares A/S, Ronald van Nooijen and Alla Kolechkina from the Technical University of Delft and Carlos Ocampo-Martinez from the Polytechnic University of Catalan for their hospitality and exchange of knowledge about the technical and research aspects related to the development of the control systems.

A special thanks to Edwin van Velzen and Jordi Cabot Ple for their help with quality assuring the parts of the paper related to these two systems. Also a special thank you to Niels Bent Johansen for his participation and contribution to inspirational discussions on sewer system control.
This project is initialized and financed by Copenhagen Wastewater Innovation and is financially supported by The Danish Agency for Science, Technology and Innovation under the Industrial PhD program (project number 11-109494). The support is greatly acknowledged.

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II

Regulatory control analysis and design for sewer systems

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Environmental Modelling and Software, Vol. 66, pp 153-166.

Regulatory control analysis and design for sewer systems

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ABSTRACT

A systematic methodology for regulatory control analysis and design is adapted for sewer system operation and evaluated.

The main challenge with adapting the methodology is the handling of the stochastic and transient nature of the rainfall disturbances, inherent to sewer system operation. To this end, four distinct modes of operation are identified (dry weather, filling, saturation and emptying) and for each of these the process gain matrix is found.

Based on the gain matrices a controllability analysis is performed, to screen for suitable pairings between measurements and actuators in the case study area of Copenhagen. The analysis effectively reduces the number of potential controlled variables, by considering the sensitivity of the measurements towards changes in the manipulated variables. Several potential pairings are generated and the best alternative is chosen for closed-loop testing.

The methodology is a promising tool for systematic generation of solutions for sewer system control.

Keywords: Sewer system control; regulatory control; controllability analysis; pairing

Abbreviations: Chicago design storm (CDS), Combined sewer overflow (CSO), condition number (CN), controlled variable (CV), frequency-dependent RGA (f.d.RGA), manipulated variable (MV), mean absolute error (MAE), relative gain array (RGA), root mean square error (RMSE), singular value decomposition (SVD), sum of squared errors (SSE), sum of the error (SE)

1 INTRODUCTION

Controlling a sewer system, such that the operation of the system is adjusted to handle the experienced disturbances, most of them being rainfall occurrences, is a way to optimize the performance of the existing structures. This can among other things lead to a decrease in the volume and frequency of CSOs and thus a reduction in the negative impact on the receiving water bodies, which is in the interest of the water utilities responsible for handling the sewerage water and ensuring the permissions for CSOs are not exceeded.

The simplest type of control for any system is often a distributed control structure with single input, single output feedback loops, also known as regulatory control (Larsson and Skogestad 2000).

In Figure 1 a sewer system process controlled by a feedback loop is illustrated. When a system is controlled by means of a feedback control loop, a measurement of the controlled variable, such as a flow or a level, is made or inferred. The estimated value of the controlled variable is then compared to the desired setpoints and by changing the setting of the actuator (i.e. adjusting the manipulated variable, such as pumps and valves), the controller aims to keep the controlled variable close to its setpoint value. The difference between the setpoint and the measured value of the controlled variable is the error, which should be close to zero. Such a control is also called closed-loop control. If the process (or system) is controlled without feedback it is called open-loop control (Seborg *et al.* 2011).

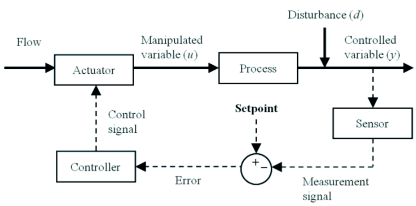

Figure 1: Feedback control loop for a sewer system. The bold lines are the physical system, while the dotted lines are signals (from Mollerup et *al*. submitted).

The control system for a sewer system can have a hierarchical architecture, with the control layers at the lower levels and the optimising layers at the higher levels (Mollerup *et al*. submitted). Although a control system with only one layer, the regulatory control layer, has a simple control structure, designing the regulatory control for a sewer system with a large number of sensors and actuators (pumps, valves, gates, etc.) is not a simple task. Examples of important questions that need to be answered include the following: 1) Which measurements to use? 2) How to pair the measurements with the available actuators?

The traditional approach used for designing a control system for sewer system operation is usually experience-based and a highly iterative process, where a large number of possible control system designs are outlined and simulation results compared to find the best solution (Beeneken *et al.* 2013). To the best of our knowledge no methodological ways of designing the regulatory control for sewer systems are published.

In the field of control engineering a methodological approach however exists that is often used in fields such as chemical engineering (Larsson and Skogestad 2000), wastewater treatment engineering (Olsson and Newell 1999, Vangsgaard *et al.* in press), etc. This approach, also called process oriented approach for control system design, employ a set of tools and methods from control and systems theory. It follows a step-by-step procedure to describe the control objective and to perform degrees of freedom analysis, screening of measurements, assessment of measurement sensitivities to changes in the inputs and pairing between measurements and inputs. Using this information the control loops are formulated and closed-loop evaluation of promising control loops are made. Finally, iterations are made if necessary.

However, adapting the methods used in the process oriented approach for control system design (tailored for the needs of process dynamics and operations in chemical and wastewater treatment engineering) to sewer system is not straightforward and requires a systems analysis approach. The main challenge in sewer system operation is the fact that the disturbances, mainly the rainfall runoffs, are highly stochastic and transient in nature which creates transient dynamics in the sewer system. Nevertheless, the tools from modern control engineering (Seborg *et al.* 2011) are in principle generic and may still provide insights into the analysis of sewer systems operation and control; provided that the methodology and the methods and tools are adapted to the specific needs of sewer system control.

In this paper a methodological approach for controllability analysis and design of regulatory control is adapted and applied to an example of a sewer system. The application of the methodology is highlighted through a case study – a subcatchment of Copenhagen's sewer system. To be able to maintain the main focus of the study on control aspects, a simulation model (Mouse mouse) of the catchment areas is used to represent and describe sewer systems input and output dynamics to highlight the application of the methodology.

The paper is organized as follows: first the methodology is described in section 2 including all the associated methods and tools; then the software used is presented in section 3 and a case study application of the methodology is presented in section 4. In section 5 the results are discussed before providing concluding remarks in section 6.

2 A SYSTEMATIC METHODOLOGY FOR REGULATORY CONTROL DESIGN - METHODS AND TOOLS

To solve a control problem two important questions needs answering, among others (Larsson and Skogestad, 2000): 1) What variables are to be controlled, manipulated and measured? 2) How should the controlled and manipulated variables be paired? To analyse and answer these questions in a structured way, a stepwise methodology is proposed that can be seen to the right in Figure 2.

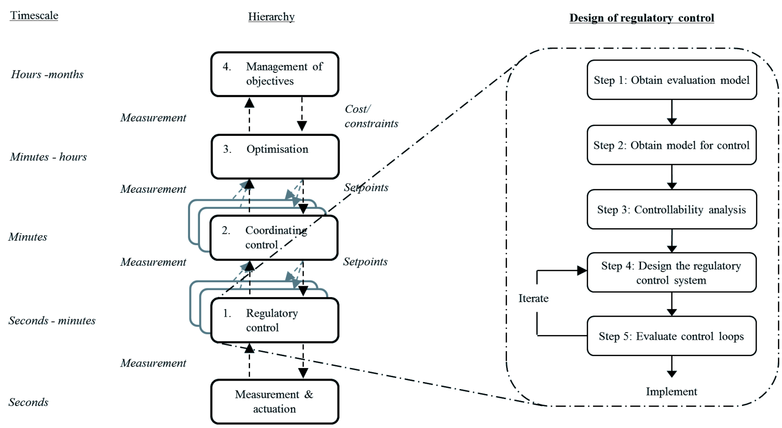

Figure 2: Methodology for design of the regulatory control layer.

The methodology presented here aims at regulatory control layer design. This task is in fact part of a larger control design problem of sewer systems, as shown in the left part of Figure 2 (from Mollerup *et al*. (submitted)).

Each of the steps of the methodology is described in the following sections 2.1 to 2.5.

2.1 *Step 1: Obtain evaluation model*

The evaluation model is a dynamic model of the system that can describe the real world with sufficient accuracy. In this context sufficient accuracy is related to the models ability to simulate overflow patterns correctly.

The model is used for evaluating the control system. To this end, detailed physically distributed first principles models such as MOUSE/MIKE URBAN (DHI group 2014), as well as lumped-conceptual models can be used (see e.g. Bach *et al.* (2014), for an overview), which relate impacts of input disturbances to system output and performance.

The detailed first principle model used by the utility company is readily available. However, the software has an inflexible control toolbox and does not easily exchange data with other systems. Therefore this model is not chosen as the evaluation model.

Instead a simple Virtual Tank model representation is selected. The Virtual Tank model is mainly based on maintaining mass balances in the system. The model is chosen because of its simplicity, which makes it relatively easy to implement using any programming language, and its linear properties, which makes it suited for testing control ideas (Ocampo-Martinez 2010).

2.1.1 Equations of the virtual tank model

The overall virtual tank model includes both virtual tanks that describe subcatchments in an area assuming precipitation and flow to be homogeneous, and real detention tanks (detention basins).

The outflow from a virtual tank (subcatchment) is based on the linear reservoir assumption:

$$q_{out} = \beta_i V_i \qquad \text{eq. (1)}$$

, where V_i is the volume of water in the tank and the parameter β_i (s^{-1}) is a volume/flow conversion coefficient. β_i can be determined from regression of historical data of flow and level. If the regression is not satisfactory for all ranges of level/flow, β_i can be determined piecewise for two or more ranges at the expense of introducing nonlinearity in eq. 1.

The mass balance for a virtual tank is expressed as:

$$\frac{dV_i}{dt} = q_{in} + I_{eff} - q_{out} \qquad \text{eq. (2)}$$

, where t is time, q_{in} is the inflow coming from other tanks, virtual tanks and the dry weather flow (household wastewater), I_{eff} is the effective rainfall runoff and q_{out} is the outflow from the virtual tank, empirically modelled as in eq. 3.

The effective rainfall is the amount of rainfall that actually goes into the sewers. The effective rainfall runoff can therefore be expressed as:

$$I_{eff,k} = A \times a \times I \qquad \text{eq. (3)}$$

, where A is the catchment area, a is the runoff coefficient (degree of connection times imperviousness) and I is the rainfall intensity.

The mass balance for a real tank is expressed as:

$$\frac{dV_i}{dt} = q_{in} - q_{out} - q_{overflow} \qquad \text{eq. (4)}$$

, where q_{in} is the inflow coming from other tanks (virtual and real), q_{out} is the outflow from the tank and $q_{overflow}$ is a potential overflow that only occurs when the tank is full and the inflow is larger than the outflow.

When the model is run in open loop, meaning with no feedback control of the pumping station, the outflow from offline detention tanks are modelled with the valve equation:

$$u_i(t) = u_{i,max} \times \sqrt{V_i(t)/V_{i,max}} \qquad \text{eq. (5)}$$

, where $u_{i,max}$ is the maximum capacity of the actuator, $V_{i,max}$ is the maximum volume of the pumping pit or basin that the actuator is emptying and $V_i(t)$ is the current volume of the pump sump or basin. The outflow from inline basins such as pipe basins is modelled in the same way as the outflow from virtual tanks (eq. 1).

The modelling of overflow is a key step, given that one of the primary objectives of sewer system control is to minimise the overflow to the environment (rivers, lakes, sea, etc.). Most basins are designed with an overflow possibility to a nearby receiving water. The overflow thus happens when the basin is full and there continues to be an inflow exceeding the outflow:

$$q_{overflow} = \begin{cases} 0 & if\ \mathrm{V} \leq V_{max} \\ q_{in} - q_{out} & \text{otherwise} \end{cases} \qquad \text{eq. (6)}$$

However, sometimes there is a need for an overflow possibility even if there is no basin. In that situation the overflow occurs when the capacity of the pipe downstream from the overflow structure is exceeded:

$$q_{overflow} = \begin{cases} 0 & if\ q_{in} \leq q_{max} \\ q_{in} - q_{max} & \text{otherwise} \end{cases} \qquad \text{eq. (7)}$$

, where q_{max} is the capacity of the downstream pipe.

Not all the overflows are discharged to the environment; overflows can also be a means of redirecting water between different subcatchments. However, the methods for modelling these internal overflows are the same.

The dry weather flow is the wastewater produced by households. The dry weather flow is modelled as a constant flow based on the number of population equivalents in each of the catchments:

$$q_{dry} = q_{PE} \times \mathrm{PE}$$

, where q_{PE} is the average discharge of water per inhabitant and PE is the population equivalents.

The dry weather flow's contribution to the total flow during large rain events can sometimes be considered negligible. Nevertheless, even during large rain events it can still be important to take the dry weather flow into account, since it is an important source of polluting agents that is mixed with the stormwater runoff and can be spilled in case of overflow. However, in this study water quality is not taken into account.

2.1.2 Calibration and validation of the model

To ensure that the virtual tank model represents the dynamics of the sewer system well enough for control analysis, the model is calibrated and validated. The parameters for calibration are the beta-values.

The calibration of these is done by a nonlinear least squares method that aims to minimise a defined objective function. The most common way to define the objective function is to calculate the sum of squared errors (SSE):

$$SSE = \sum_{i=1}^{N}\sum_{i=1}^{n}\left(\boldsymbol{y}_{i,j} - f(\boldsymbol{x}_{i,j},\boldsymbol{\theta})\right)^2 \qquad \text{eq. (8)}$$

, where N is the number of rain events used in the calibration, n is the number of observations in each event, $\boldsymbol{y}_{i,j}$ are the observations and $f(\boldsymbol{x}_{i,j},\boldsymbol{\theta})$ are the model results.

However, using the SSE for calibration might optimise the timing of the overflows at the expense of keeping the volume of the overflow correct. It is important to calibrate the model to have both a good fit with respect to the timing and to the volume of the overflows. Since a change in the beta value affects both the time the overflow starts as well as the volume, it is not possible to calibrate both, with only the beta values, if there is a structural problem with the model.

Another way of defining the objective function is to minimise the difference between the observed and the simulated overflow volumes for each event, to emphasize on minimising the sum of the error (SE) on the volume of the overflows:

$$SE = \sum_{i=1}^{N}\left|\sum_{j=1}^{n}\boldsymbol{y}_{i,j} - \sum_{j=1}^{n} f(\boldsymbol{x}_{i,j},\boldsymbol{\theta})\right| \qquad \text{eq. (9)}$$

To validate the model three different statistical indicators are calculated (Power 1993; Sin *et al.* 2007, Bennett *et al.* 2013): i) Mean absolute error (MAE) that should be as small a value as possible, ii) Root mean square error (RMSE) that should also be as small a value as possible and iii) the Janus coefficient (J) that should be close to one.

$$\text{MAE} = \frac{1}{m}\sum_{i=1}^{m}\left|\boldsymbol{y}_i - f(\boldsymbol{x}_{i,j},\boldsymbol{\theta})\right| \qquad \text{eq. (10)}$$

, where m is the number of observations ($m = n_1 + n_2 + \cdots + n_N$), y_i are the observations and $f(\boldsymbol{x}_i)$ are the model results.

$$\text{RMSE} = \sqrt{\frac{1}{\text{m}}\sum_{\text{i}=1}^{\text{m}}\left(\boldsymbol{y}_i - f(\boldsymbol{x}_{i,j}, \boldsymbol{\theta})\right)^2} \quad \text{eq. (11)}$$

$$J = \text{RMSE}_{\text{val}}/\text{RMSE}_{\text{cal}} \quad \text{eq. (12)}$$

, where the indices val and cal refers to the RMSE calculated on the basis of the validation and the calibration dataset, respectively.

2.2 *Step 2: Obtain model for control*

To be able to analyse the interactions between the possible control loops in the system, a controllability analysis is performed. However, most tools used in control engineering for controllability analysis (such as singular value decomposition and relative gain array (RGA)), need a transfer function model that describe the relationship between the inputs ($\boldsymbol{u}_i$) and the outputs ($\boldsymbol{y}_i$) of the system through a gain matrix (Seborg *et al.* 2011). It can be either a steady-state gain matrix or a transfer function gain matrix. The latter is required if the system dynamics are important to consider. A gain transfer model is depicted in Figure 3, where $G(s)$ is the transfer function gain matrix that represents the system dynamics in the Laplace domain (frequency domain).

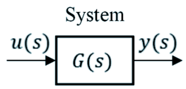

Figure 3: Transfer function model in the Laplace domain.

Analysing the system based on the gain matrix can be done both in the time and the frequency domain. However, complimentary insight can often be obtained from analyses done in the frequency domain. The tools and analyses used here are therefore done in the Laplace domain.

For a dynamic system the transfer function model in the Laplace domain can be expressed in vector-matrix notation as:

$$\boldsymbol{Y}(s) = \boldsymbol{G}(s)\boldsymbol{U}(s) \quad \text{eq. (13)}$$

, where $\boldsymbol{G}(s)$ is the transfer function matrix, $\boldsymbol{U}(s)$ is the input matrix and s is the Laplace variable.

In the time-domain, the input and output dynamics are represented by state-space formalism as follows: (Seborg *et al.* 2011):

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \qquad \text{eq. (14)}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \qquad \text{eq. (15)}$$

Where $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ are matrices, $\boldsymbol{x}$ are the states, $\boldsymbol{u}$ are the inputs and $\boldsymbol{y}$ are the outputs.

The relationship between the state-space representation and the transfer function model follows (Seborg *et al.* 2011):

$$\boldsymbol{G}(s) \triangleq \boldsymbol{C}[s\boldsymbol{I} - \boldsymbol{A}]^{-1}\boldsymbol{B} \qquad \text{eq. (16)}$$

, where I is the identity matrix.

Indeed both model types can be used for controllability analysis.

There are several approaches to obtain a linear dynamic model for control studies including Taylor series approximation of nonlinear system models versus perturbation (step change) experiments at different operation points at the physical system (Seborg et al 2011). In this study, given the availability of nonlinear model of the system, a first order Taylor approximation method is therefore used to obtain the models to perform control studies (both in state-space and Laplace domain) using the model identification toolbox in Matlab/Simulink (see section 3)."

The above mentioned methods require the definition of a steady-state operation point for the system, at which the model identification analysis will be performed. However, due to the transient nature and size of the disturbances in sewer systems, these systems do not have a steady state and thus it is not possible to determine an equilibrium point. This challenge is addressed by building a number of control models at different time intervals corresponding to different characteristics in sewer system input and output dynamics. This is shown in Figure 4.

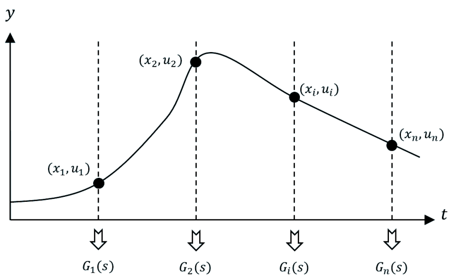

Figure 4: Conceptual representation of how the transfer function model is obtained at different operating points.

2.3 *Step 3: Controllability analysis*

The aim is to design a regulatory control layer that is efficient. Thus there should be minimum interactions between the different control loops of manipulated and controlled variables, while still maintaining a high sensitivity between the controlled variable and the manipulated variable of the individual control loops. Controllability analysis is used to identify the most efficient pairing, through single value decomposition (SVD) analysis and the calculation of the relative gain array (RGA).

For the purpose of performing the SVD and calculating the RGA the transfer function model needs to be evaluated at a certain operating point, s, since these analyses are based on the gain matrix:

$$\boldsymbol{G_s} = \boldsymbol{Y_s}/\boldsymbol{U_s} \qquad \text{eq. (17)}$$

, where $\boldsymbol{Y}_s$ and $\boldsymbol{U}_s$ are the output and the input, respectively, at a certain operating point s.

2.3.1 Obtaining the gain matrices

The gain matrices are obtained by applying eq. 17 to the transfer function models, where the Laplace variable is substituted with $s = j\omega$ (Seborg *et al.* 2011), ω being the frequency and j being any arbitrary number, here chosen as 1.

To select the frequency, ω, it can be useful to do a frequency analysis of the disturbance, to find out if it has a dominating frequency, as discussed by Mauricio-Iglesias *et al.* (submitted). The alternative to a spectral analysis of disturbances is to choose the frequency from operational understanding.

Once the gain matrices are obtained, they are scaled, to ensure the gains have comparable units. This is done by dividing each input and output by its corresponding range (Seborg *et al.* 2011).

2.3.2 Singular value decomposition

The condition number (CN) is a way to determine the best subset of measurements to be paired with the manipulated variables. It is calculated by looking at the relationship between the maximum and the minimum singular value of the gain matrix (Seborg *et al.* 2011). By dividing the largest singular value by the smallest singular value, it is tested if the system is well conditioned. In the context of the optimal pairing of controlled variables with manipulated variables for the design of regulator control layer, a low condition number for a given pairing candidate indicates that the controlled variables can be regulated independently of each other. That is to say that interaction between control loops is low which is desirable for regulatory control system design (Seborg et al. 2011).. Thus based on the condition number of the individual subsets of measurements, the subset(s) best suited for further analysis can be chosen.

Since the gain matrix, $\boldsymbol{G_s}$, relates the available measurements to the manipulated variables of the system, it will have a number of rows equal to the number of measurements and a number of columns equal to the number of manipulated variables. However, the CN is calculated for square matrices, and thus must be calculated for every combination of measurements and actuators:

$$\mathrm{CN} = \frac{\sigma_{max}(\boldsymbol{G}_{s,nxn})}{\sigma_{min}(\boldsymbol{G}_{s,nxn})} \qquad \text{eq. (18)}$$

, where σ is the singular values of the transfer function gain matrix, $\boldsymbol{G}_{s,nxn}$, which is a square subset of $\boldsymbol{G}_s$ with the number of rows and columns equal to the number of manipulated variables.

2.3.3 Calculation of the relative gain array

The relative gain array (RGA) is the second, alternative method used to find the best pairing between measurements and actuators. The general relative gain array is calculated from the steady-state gain matrix. However, for a process with time delays the process dynamics can be important in the pairing decisions. Therefore the frequency-dependent RGA (f.d. RGA) is calculated here instead, where the calculation is based on the gain matrix instead of the steady-state gain matrix. The frequency-dependent RGA can be calculated for a square matrix as follows (Bristol 1966):

$$\mathrm{f.d.\,RGA} = \left(\boldsymbol{G}_s{}^{T}\right)^{-1} \otimes \boldsymbol{G}_s \qquad \text{eq. (19)}$$

Here subsets of measurements have been selected using the CN, and therefore the system is described by a square matrix. Alternatively, one could calculate the non-square RGA for non-square systems, which provides similar insights for pairing between inputs and outputs (Chang and Yu 1990).

For the pairing one should avoid negative relative gains and very large relative gains. A good pairing is indicated by a relative gain close to 1.

2.4 *Step 4: Design the regulatory control system*

Based on the calculations of the CN and the f.d.RGA, the potential pairings can be selected for evaluation, thereby formulating the control loops for the regulatory layer.

Once a pairing is selected for a control loop, the next step is to define the control law. For the regulatory control layer, the feedback control law is usually used. The simplest form of the feedback controllers is the proportional controller (Seborg *et al.* 2011):

$$u(t) = \bar{u} + K_c\big(y(t) - y_{SP}(t)\big) \qquad \text{eq. (20)}$$

, where $y(t)$ is the measured value of the controlled variable, $y_{SP}(t)$ is the setpoint for the controlled variable, $\bar{u}$ is the steady state value or nominal value of the input and K_c is the proportional gain.

Once the control law is defined, the control parameters need to be tuned. For models in the form of $\boldsymbol{G}(s) = K/s$, the Internal Model Control technique can be used to tune the controller gain parameter, K_c (Seborg *et al.* 2011):

$$K_c = 2/(K\tau_c) \qquad \text{eq. (21)}$$

, where τ_c is the desired closed-loop time constant, which is a tuning parameter.

Finally, the setpoints for the controllers need to be determined. This is usually determined by upper layers of the control structure (Mollerup *et al.* submitted). The setpoints can be determined from either operational knowledge, simulations combined with trial-and-error or optimisation (offline or online). However, this paper only investigates how the regulatory layer can be designed. Therefore it is not within the scope of the paper to determine if a higher layer controller or online optimisation could improve the control, by adjusting the setpoint over time.

Regardless of the method for obtaining the setpoints, the goal should remain the same: To choose the setpoints that will minimise the objective function defined for sewer system operation. How to specify the objective function is another design degree of freedom. Here it is chosen to focus on the total CSO volume:

$$\text{tot CSO} = \sum_{i=1}^{m}\sum_{j=1}^{k}\boldsymbol{y}_{i,j} \qquad \text{eq. (22)}$$

, where m is the number of simulation time steps, k refers to the location of overflow and $\boldsymbol{y}_{i,j}$ is the overflow observation.

Alternatives could be to minimize the frequency of the CSOs or the duration of the CSOs. Also the individual CSOs could be weighted according to importance, etc. (Schütze *et al.* 2004; Van Nooijen *et al.* 2011).

2.5 *Step 5: Evaluate control loops*

The control structure is evaluated in two ways: 1) with respect to stability, 2) performance of the closed-loop compared to open-loop operation.

To evaluate the stability of the control loops, the system is simulated with the disturbance of a single event and the results are assessed visually.

To compare the closed-loop operation with the open-loop, a simulation of a historic rain series of 10 years is performed and the total overflow is calculated (eq. 22) as well as the total overflow for each of the overflow locations:

$$\mathrm{CSO}_m = \sum_{i=1}^{n} \boldsymbol{y}_{m,i} \qquad \text{eq. (23)}$$

, where n is the number of simulations time steps, m refers to the location of overflow and $\boldsymbol{y}_{m,i}$ is the overflow.

3 SOFTWARE FOR MODELLING AND CONTROL

The implementation of the virtual tank model is done in Matlab/Simulink (version 2012b), due to the control toolboxes readily available in this software.

The parameter estimation described in section 2.1.2 is done using eq. 8 and 9. In Matlab this is done using the function *fminsearch*, which is a local, nonlinear, unconstrained optimisation method. The function works by minimising a cost function defined by the user.

The Simulink Control Design Linearization Tool is used to perform model identification, described in section 2.3. To obtain the state-space formulation of the model (eq. 14 and eq. 15), the virtual tank model of the sewer system is linearized block-by-block, at different time steps corresponding to different operating points, using the snapshot tool of Simulink.

To get the model converted into the frequency domain as in eq. 16, the function *tf* is used to get the transfer function notation.

The Matlab function *freqresp* is used to calculate eq. 17, which is the gain matrix at a specified frequency. Matlab/Simulink scripts and models used in this work can be obtained from the authors upon request.

4 CASE STUDY

A small but representative case study was selected to motivate and highlight the step-wise application of the methodology to sewer systems.

The methodology is applied on a subcatchment of Copenhagen's sewer system owned and maintained by HOFOR[1]. It has a size of 320 hectare and is equipped with 3 pumping stations, 2 storage tanks, 1 pipe basin and 5 CSO structures (see Figure 6, left). The disturbances to the system are the sewerage (dry weather flow) and the rainfall runoff.

4.1 *Step 1: Obtain evaluation model for the sewer system*

The sewer system is modelled in Matlab using the virtual tank model. A schematic representation of the case area model is shown in Figure 5.

[1] Hovedstadsområdets Forsyningsselskab (in Danish).

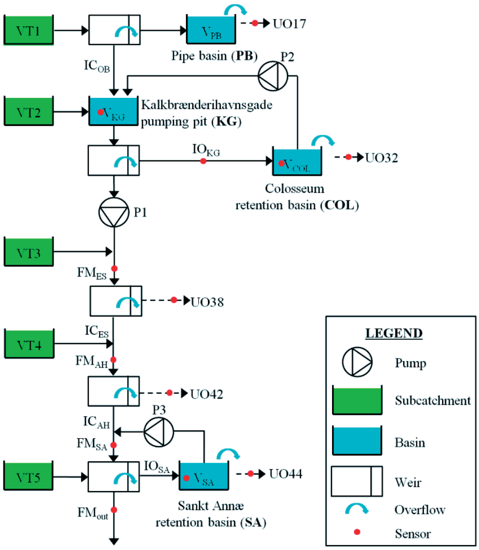

Figure 5: Schematic representation of the virtual tank model of the case study area. The symbols used are: VT = Virtual tank, P = pumping station, UO = External overflow, IO = Internal overflow, FM = Flow measurement, IC = Interceptor capacity.

Figure 5 shows four basins. Two of those are offline basins: Colosseum and Sankt Annæ. The third basin is an inline pipe basin, while the last basin is just a large pumping pit for Kalkbrænderihavnsgade Pumping Station.

4.1.1 Determination of system attributes

The majority of the model parameters are actual system attributes and are determined from the design of the system. Those parameters are the subcatchment areas, the dry weather flow, the interceptor pipe capacities, the volumes of the basins and the capacity of the pumps. The values are shown in Table 1.

The subcatchment areas (Figure 6, right) are obtained from a MOUSE model of the system. The MOUSE data is estimated from a geographical information system and has been calibrated against flow measurements. The location of the subcatchments is illustrated in Figure 6 (right).

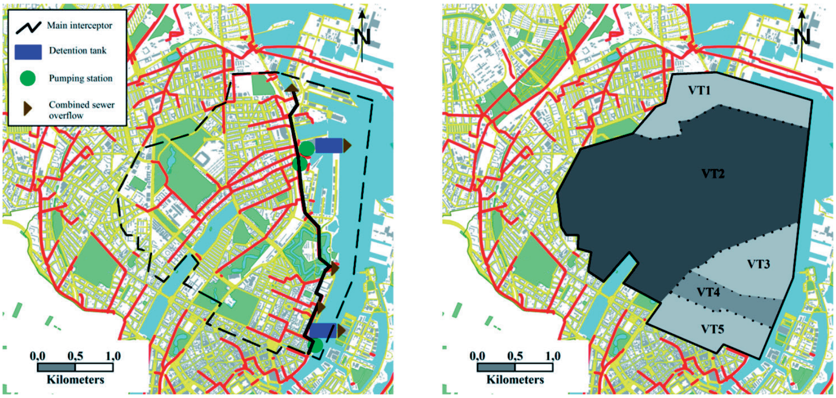

Figure 6: Map of case study area. To the left is a map of the sewer system structure and to the right is a map of the subcatchments.

The dry weather flows are determined from existing estimations of these.

The real tanks, the detention basins, have volume as a parameter and these are taken from the MOUSE model.

The capacities of the interceptor pipes are found from diagrams of full running sewer pipes (Winther *et al*. 2011), where the dimensions and slopes of the pipes come from the MOUSE model.

Finally the maximum capacity of the pumps comes from operational knowledge. The pumps are all frequency regulated. They are modelled as perfect actuators, setting the flow to the desired value immediately.

Table 1: Virtual Tank model parameters.

Subcatchments	VT1	VT2	VT3	VT4	VT5
A [ha]	23.5	222.5	30.0	8.2	33
q_{dry} [l/s]	29	1035	178	200	2
Retention basins	PB	KG	COL	SA	
V [1000 m^3]	0.61	1.60	35.72	7.05	
Interceptor pipes	IC_{OB}	IC_{ES}	IC_{AH}	F_{out}	
q_{max} [l/s]	400	900	1000	1000	
Pumps	P1	P2	P3		
u_{max} [l/s]	900	500	300		

The only parameter that cannot be determined from the design of the sewer system, because it is not related to a single physical property of the system, is the volume/flow conversion coefficient (the beta parameter). Instead this needs to be calibrated.

4.1.2 Model calibration and validation

The existing sewer system has control implemented, which makes it difficult to obtain operational data for calibration. The reasons for this are 1) the overflows have a rather high return period (T = ½-1 year) and therefore many years of data is needed to obtain a sufficient number of events needed for the calibration, 2) The implemented control has been altered several times over the last decade due to structural changes and changes in the control strategy. As a result it is not possible to obtain a sufficiently long period of operational data to be used for automatic model calibration.

Instead data for the calibration and validation of the virtual tank model is found from simulations of the case study area with a MOUSE 2009 model. The MOUSE model is used by the utility company for urban drainage planning and is therefore assumed to be able to describe the model dynamics of the system for the purpose of this project.

The MOUSE model is run with the implemented control and the trajectories of the pumps are used in the Matlab model as an input, to ensure that any model errors does not come from differences in how the control is simulated.

As mentioned in section 2.1.2 the choice of objective function for the calibration can possibly affect the result. It is therefore decided to calibrate the model in two different ways, using eq. 8 and 9, respectively. The results can be seen in Appendix A.

To test which of the calibrations yield the best results, three different statistical indicators are calculated using eq. 10 to 12: i) Mean average error (MAE) that should be as small a value as possible, ii) Root mean square error (RMSE) that should also be as small a value as possible and iii) the Janus coefficient (J) that can vary between zero and ∞ and should be close to one (Power 1993).

The statistical indicators show that the calibration done by minimising the SSE (eq. 8), results in the best parameter estimation. In Table 2 the statistical indicators based on the SSE calibration can be seen.

Table 2: Statistics on the model fit when the parameter estimation is done based on SSE.

Parameter	Measurements		No. of observations	MAE	RMSE	J
			[-]	[m^3/s]	[m^3/s]	[-]
β_{VT1}	UO17	Calibration	3806	0.02	0.10	0.96
		Validation	5003	0.01	0.09	
β_{VT2}	UO32	Calibration	3806	0.21	0.65	0.60
		Validation	5003	0.13	0.39	
β_{VT3}	UO38	Calibration	3806	0.08	0.21	0.59
		Validation	5003	0.03	0.13	
β_{VT4}	UO42	Calibration	3806	0.03	0.11	0.58
		Validation	5003	0.01	0.06	
β_{Vt5}	UO44	Calibration	3806	0.10	0.28	0.65
		Validation	5003	0.04	0.18	
β_{PB}	UO17	Calibration	3806	0.02	0.10	0.96
		Validation	5003	0.01	0.09	

From Table 2 it can be seen that the MAE and RMSE values are all close to zero, meaning that there is no systematic deviation from the observations. The Janus coefficients are around 0.6 or higher. The Janus coefficient tells us if the model structure has remained the same; a value of 0.6 means that the RMSE has changed 40 % in the validation from the calibration, which is considered acceptable in wastewater modelling (Sin *et al.* 2007, Ghorbani and Eskicioglu 2011).

When visually comparing the model predictions with the MOUSE results it can be seen that to a large extend the model captures the dynamics of the overflows. In Figure 7 the simulation results of the ninth rain event is shown, as this event results in overflows from most of the overflow structures (to see plots of all the simulation results see Appendix B).

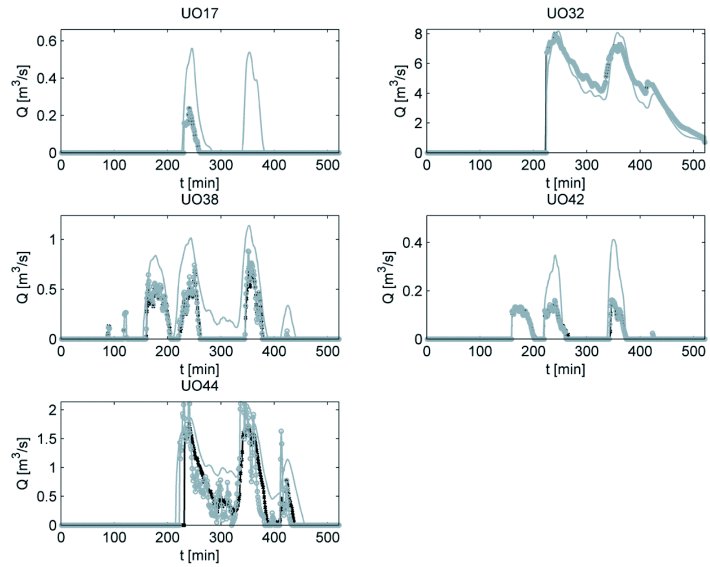

Figure 7: The simulation results of the ninth rain event used in the validation. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

As exemplified in Figure 7 it can be seen that there are differences between the Mouse model results and the results from the virtual tank model. However, overall the Virtual Tank model is able to describe the main dynamics related to the overflows. Especially the dynamics of two overflows from the large retention basins (UO32 and UO44) and the overflow downstream from Kalkbrænderihavnsgade Pumping Station (UO38) are well captured by the Virtual Tank model, which is important, since these are the overflows that can be affected by adding control.

Based on the results the validation is considered acceptable. The virtual tank model is able to describe the main dynamics of the case study sewer system in both the calibration and validation period. Therefore the model is considered suitable for the purpose of this study to be used for the control analysis as well as for the final evaluation of the control.

4.2 *Step 2: Obtain model for control*

From the virtual tank model, a linear model is obtained using the build in tools of Matlab Simulink. The disturbance used for this purpose is the same CDS rain as used for the initial calibration of the virtual tank model parameters (section 4.1.2).

4.2.1 Obtaining piecewise linear models

As described in section 2.2 the linearisation is done at different time steps (t) during the simulation of a rain event. Because of the large transients during the rain event, it is chosen to do the linearisation every 30 minutes during the duration of the event. After the end of the rain event and until the system is back to the operational conditions during dry weather, the system linearisation is done every 120 minutes (for the full results please obtain the additional material as described in section 8). The simulation results and the linearisation points can be seen in Figure 8.

The states $(\boldsymbol{x}_i)$, inputs $(\boldsymbol{u}_i)$ and outputs $(\boldsymbol{y}_i)$ of the state-space model (eq. 14 and 15) can be seen in Table 3 (to see the full results please obtain the additional material).

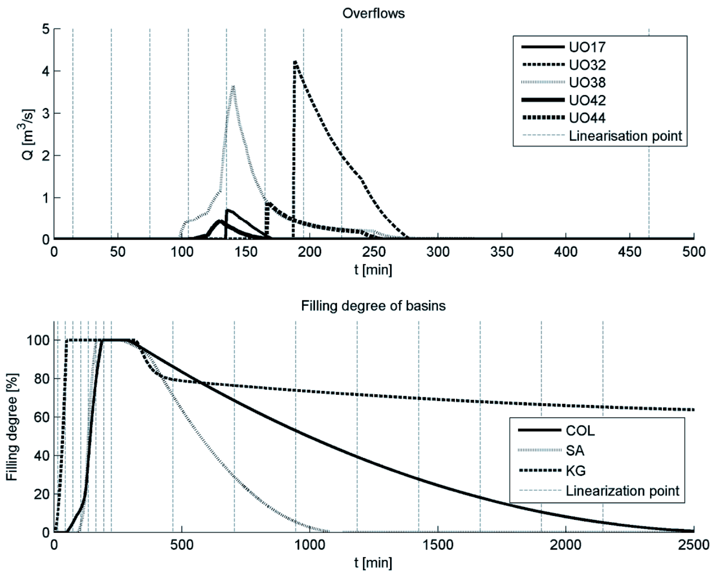

Figure 8: Simulation results with open loop, CDS, T = 5 years (NB the scaling of the horizontal axis is different in the two plots).

Table 3: The states, inputs and outputs of the state-space model (the names of variables correspond to those used in Figure 5).

i	1	2	3	4	5	6	7	8	9	10	11	12	13
$\boldsymbol{x}_i$	V_{COL}	V_{KG}	V_{SA}										
$\boldsymbol{u}_i$	P_1	P_2	P_3										
$\boldsymbol{y}_i$	FM_{ES}	FM_{AH}	FM_{SA}	U032	V_{COL}	IO_{KG}	V_{KG}	U017	U044	V_{SA}	U038	U042	FM_{out}

4.2.2 Obtaining the transfer function gain matrices

Using Matlab's tool for converting a model from the state-space domain to the Laplace domain the linear model is transformed to the frequency domain. To model the retention tanks, the linearised model has a few integrators (with s in the denominator and a scalar value in the numerator), but other than that it consists of constant gains (see Table 4). However, the system is still rather complex, because the transfer function gain matrices at the different linearisation points are different due to the different nominal conditions used.

Looking at the linearisation results it is found that the transfer function gain matrices are the same for several of the linearisation points. Based on the results it is therefore chosen to categorize the sewer system operation in four operational modes. Within these four operational phases slight variations in the scalar values of the transfer function gain matrices do occur, but the structure remains the same and therefore the transfer function gain matrix can be considered the same for the purpose of the controllability analysis. The four different modes of operation that are identified are: 1) dry weather, 2) filling, 3) saturation and 4) emptying.

The resulting transfer function matrices can be seen in Table 4, where it is also indicated the first and last linearisation point included in the different operational modes (to see the linearised models at each time step please obtain the supplementary material).

Table 4: The transfer function gain matrices for the different operational modes. The time period, t (min), for each phase is shown in parentheses.

	Dry weather (t = 0 - 45)			Filling (t = 75 - 165)			Saturation (t = 195 - 225)			Emptying (t = 465 - 2500)		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
FM_{ES}	1	0	0	1	0	0	1	0	0	1	0	0
FM_{AH}	1	0	0	1	0	0	1	0	0	1	0	0
FM_{SA}	1	0	1	1	0	1	1	0	1	1	0	1
UO32	0	0	0	0	0	0	-1	2 e-11	0	0	0	0
V_{COL}	0	-1/s	0	-1/s	(-3 e-10)/s	0	0	0	0	0	-1/s	0
IO_{KG}	0	0	0	-1	1	0	-1	1	0	0	0	0
V_{KG}	-1/s	1/s	0	0	0	0	0	0	0	-1/s	1/s	0
UO_{17}	0	0	0	0	0	0	0	0	0	0	0	0
UO_{44}	0	0	0	0	0	0	0	0	0	0	0	0
V_{SA}	0	0	-1/s	0	0	-1/s	0	0	0	0	0	-1/s
UO_{38}	0	0	0	0	0	0	0	0	0	0	0	0
UO_{42}	0	0	0	0	0	0	0	0	0	0	0	0
FM_{out}	1	0	1	1	0	1	1	0	1	1	0	1

From the results in Table 4 it can be seen that the gain matrices all consists of either a scalar value or a fraction (integral gain). It can also be seen that the transfer function gain matrices contain gains with both positive and negative signs. If the scalar value is positive, then a positive change in the input will also affect the output in a positive direction. On the other hand if the scalar value is negative a positive change in the input with affect the output in a negative direction.

Where the relationship between the input and the output of the model is described by a scalar value, the change in the output of the model is a direct function of the change in the input, with the magnitude of the scalar value.

Where the relationship between the input and the output of the model is described by an integral gain, there is a tank acting as an integrator in the system, so a change in the input to the model only affects the change in the output by a fraction of the value and thereby acting as a delay function, which is expected from a tank that acts as a buffer to incoming flows before overflowing.

Looking at the transfer function gain matrix of each of the operational modes independently it can be seen from the results of Table 4 that during the dry weather phase, the rainfall is negligible and the tanks are empty. Since the disturbance acting on the system is negligible, the manipulated variables are able to reject the disturbance. This means that there is no overflow to the two offline retention tanks and the volume of the pumping pit of Kalkbrænderihavnsgade, V_{KG} (see Figure 5 for an overview of the system), is kept below its maximum, which can also be seen from Figure 8. As a result the volume, V_{KG}, can be modelled by an integrator.

Initially it was found surprising that the volume in Colosseum (V_{COL}) is hardly influenced by the outflow from the basin (P2) during the filling phase. However, this can be explained by the fact that the operational mode changes from dry weather to filling when the pumping pit of Kalkbrænderihavnsgade (V_{KG}) becomes saturated at its maximum value. As the pumping pit of Kalkbrænderihavnsgade becomes saturated, a recirculation loop is closed, where the water from Colosseum (P2) will simply circulate back, if the tank (V_{COL}) is emptied. The implication of this is that the volume in Colosseum (V_{COL}) is no longer influenced by the outflow from the basin (P2); since the pumping pit of Kalkbrænderihavnsgade (V_{KG}) is full, a change in the outflow from Colosseum (P2) will mainly result in a change in the overflow to Colosseum (IO_{KG}). Therefore, when the recirculation loop is closed, the volume of Colosseum (V_{COL}) is instead affected by changes in the outflow from Kalkbrænderihavsgade (P1).

In retrospect it could be considered obvious that this is the expected dynamic behaviour related to offline tanks, when downstream bottlenecks are present. However, it was not evident from the beginning that this dynamic would occur already during the filling phase. Therefore, it is found that looking at the transfer function gain matrix is helpful in identifying where and when recirculation loops will be closed.

The third operational mode is while the system is completely saturated at its maximum values, meaning that the retention basins Colosseum and Sankt Annæ (V_{COL} and V_{SA}) are full, resulting in overflows to the environment.

The last operational mode is after the peak of the rain event, when the disturbance acting on the system is once again very small and there are no longer overflows to the basins. Because there is once again transport capacity in the system, the retention basins start to empty. Interestingly, the dynamics during the emptying mode are the same as during the dry weather mode, as the linear models are identical.

From Table 4 it can be seen that the transfer function gain matrices capture the expected correlations between the manipulated variables as well as which measurements are sensitive towards changes in these.

However, it should be noted that it was decided to look at the operational modes in a system-wide manner, meaning it is assumed that switches between the operational modes occur at the same time for all the controlled variables, where in reality they occur at slightly different time steps, even when the rain event is considered homogeneously distributed over the catchment. To account for these differences, the operational modes can be determined individually for each of the manipulated variables, if needed.

4.3 *Step 3: Controllability analysis*

Based on the obtained transfer function models the controllability analysis can be performed. This is done in the following section.

4.3.1 Obtaining the gain matrices

From the results in Table 4 it can be seen how the choice of frequency will affect the values of the gain matrix. With all other gains being constants, only the gains related to the retention tank volumes are affected, since these are modelled as integral gains. This means that the lower the frequency, the higher the gains for the tank volumes. For control purposes high gains are preferred, since this indicates a high degree of controllability of the measured variable.

Therefore the selection of an appropriate input frequency to evaluate the system input-output dynamics is important. To this end, a spectral decomposition of input disturbances is a commonly used method (Thornhill and Horch 2007). Since rain events are stochastic in nature, the spectral analysis reveals a uniformly distributed output response at different input frequencies, i.e. there is no dominant frequency in the input disturbances (Mauricio-Iglesias *et al.* submitted). As this is the case, the knowledge of the dynamics of the system is used to determine a suitable frequency.

In the design or retrofitting of a sewer system using the Rational method, the dimensioning is based on the maximum, average intensity over the critical time span, which is determined from the time of concentration (flow time in the system) (Winther *et al.* 2011). Based on a similar approach the frequency is chosen as the shortest critical time of concentration for the locations of the three actuators. This corresponds to the inverse of the largest flow conversion coefficient for the virtual tanks, $\beta_3 = 0.1036\ \ 1/\mathrm{min}$ $(= 9.65\ \mathrm{min})$. In the frequency domain this corresponds to 0.65 rad/min.

The gain matrices for the different operational modes are obtained by applying eq. 16. The resulting transfer function gains ($G(s = 0.65)$) can be seen in Table 5 and describes the relationship between the inputs and the outputs (eq. 13).

Table 5: The absolute values of the gains calculated for a frequency of 0.65. Prior to scaling.

	Dry weather (t = 0 - 45)			Filling (t = 75 - 165)			Saturation (t = 195- 225)			Emptying (t = 465 - 2500)		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
FM_{ES}	1	0	0	1	0	0	1	0	0	1	0	0
FM_{AH}	1	0	0	1	0	0	1	0	0	1	0	0
FM_{SA}	1	0	1	1	0	1	1	0	1	1	0	1
UO32	0	0	0	0	0	0	-1	2e -11	0	0	0	0
V_{COL}	0	-1.5	0	-1.5	-5e -10	0	0	0	0	0	-1.5	0
IO_{KG}	0	0	0	-1	1	0	-1	1	0	0	0	0
V_{KG}	-1.5	1.5	0	0	0	0	0	0	0	-1.5	1.5	0
UO_{17}	0	0	0	0	0	0	0	0	0	0	0	0
UO_{44}	0	0	0	0	0	0	0	0	0	0	0	0
V_{SA}	0	0	-1.5	0	0	-1.5	0	0	0	0	0	-1.5
UO_{38}	0	0	0	0	0	0	0	0	0	0	0	0
UO_{42}	0	0	0	0	0	0	0	0	0	0	0	0
FM_{out}	1	0	1	1	0	1	1	0	1	1	0	1

It should be noted that a choice was made here, to use the shortest time of concentration. One of the difficult tasks of performing this type of controllability analysis is that though the source of the disturbance can be assumed the same for all parts of the system (i.e. the rainfall is assumed homogenously distributed over the whole catchment), the experienced disturbance at the individual locations of the system, are different, due to the possibly wide geographical distribution of the sewer system.

Next, the transfer function gain matrices are scaled with respect to the maximum value of the manipulated variable and the maximum experienced value of the controlled variable. The results can be seen in Appendix C.

Scaling the gains has a large influence on the values of the gains related to the volumes of Sankt Annæ (V_{SA}) and Colosseum (V_{COL}), respectively. This was expected since the volumes are very large compared to the maximum outflow of the actuators, P2 and P3. Thus the volumes of the tanks are not very sensitive to changes in the manipulated variables.

Finally a sensitivity based screening is performed. Accordingly measurements that are not sensitive to changes in the manipulated variables are removed from the gain matrix.

This reduces the number of measurements relevant for regulatory control purposes from 13 to around 6 or 7, depending on the operational mode one looks at. This effectively means that the number of possible pairings is reduced from 286 to 35, which is a significant reduction in the number of pairings to further investigate.

4.3.2 Singular value decomposition

Using eq. 18 the CN is calculated for all combinations of all three actuators and subsets of three measurements. Using the single value decomposition analysis the number of pairings that are interesting to further investigate is reduced from 35 to 4. The subsets that results in a CN lower than 20 can be seen in Table 6.

Table 6: The condition number for the pairings of all the actuators with the displayed subsets of measurements (for CN < 20).

Operational mode / Subsets no.	1	2	3	4
Dry weather	FM_{ES} FM_{SA} V_{KG}			
	10.08			
Filling	FM_{ES} FM_{SA} IO_{KG}	FM_{AH} FM_{SA} IO_{KG}		
	7.27	13.01		
Saturated	FM_{SA} UO32 IO_{KG}	FM_{ES} FM_{SA} IO_{KG}	FM_{AH} FM_{SA} IO_{KG}	
	7.26	7.27	13.01	
Emptying	FM_{ES} FM_{SA} V_{KG}			
	10.08			

From the results in Table 6 it can be seen that the subsets are the same during the operational modes dry weather and emptying and again they are very similar during filling and saturation. For each of the operational modes, the subset with the lowest CN is selected for further analysis, except for during the saturated mode. Here the difference between the two lowest condition numbers is negligible, so the subset with the second lowest condition number is chosen, since this is the same as during the filling mode.

Using eq. 19 the f.d. RGA is calculated for the selected subset during each of the operational modes. For all operational modes the off-diagonal elements of the f.d. RGA are equal to zero. The results can be seen in Table 7.

Table 7: Frequency dependent relative gain array

	Dry weather			**Filling**			**Saturation**			**Emptying**		
	FM_{ES}	V_{KG}	FM_{SA}	FM_{ES}	IO_{KG}	FM_{SA}	FM_{ES}	IO_{KG}	FM_{SA}	FM_{ES}	V_{KG}	FM_{SA}
P1	1	0	0	1	0	0	1	0	0	1	0	0
P2	0	1	0	0	1	0	0	1	0	0	1	0
P3	0	0	1	0	0	1	0	0	1	0	0	1

4.4 *Step 4: Design the control*

Based on the controllability analysis the pairings between the manipulated variables (MVs) and the controlled variables (CVs) are selected as shown in Table 8.

Table 8: The selected pairing (the operational modes in which the loops are active are indicated in bold. See explanation in the text below the table).

	Control loop 1	**Control loop 2**	**Control loop 3**
	MV1 – CV1	**MV2 – CV2**	**MV3 – CV3**
Dry weather	$\mathbf{P1 - FM_{ES}}$	$P2 - V_{KG}$	$P3 - \_FM_{SA}$
Filling	$\mathbf{P1 - FM_{ES}}$	$P2 - IO_{KG}$	$P3 - FM_{SA}$
Saturation	$\mathbf{P1 - FM_{ES}}$	$P2 - IO_{KG}$	$P3 - FM_{SA}$
Emptying	$\mathbf{P1 - FM_{ES}}$	$\mathbf{P2 - V_{KG}}$	$\mathbf{P3 - FM_{SA}}$

Looking at the pairing in Table 8 it can be seen that for both P1 and P3 the pairings are the same for all operational modes. However, the controllers are not all active during all operational modes, which is also indicated in Table 8.

For P2 the pairing changes, since the controlled variable chosen during dry weather and emptying, V_{KG}, is saturated at its maximum value during filling and saturation. It is therefore not a useful controlled variable at all times. However, this does not affect the design of the controller, since the controllers for both control loop 2 and 3 are only active during the emptying phase.

The manipulated variables, P2 and P3, empty offline basins. Since these are empty during the dry weather phase, due to no inflow, the controllers are not active during these phases.

During a rain event the interceptor pipes become saturated at their maximum capacity, leading to internal overflows to the basins and the start of the filling phase. However, as the basins empty back to the system at the locations of the bottlenecks, the basins cannot empty, until the system moves to the emptying phase, where the interceptor pipes are no longer saturated. Therefore the controllers are not active during the filling and saturation phases either.

Control loop 1 is different, because the flow to P1 is continuous. The control loop is therefore active during all four phases.

Control loops 1 and 3 have flows as both the controlled and the manipulated variable. Because of the transient nature of the disturbances, it is however not possible to select a nominal input, $\bar{u}$, that leads to a stable P-controller for these loops. Instead eq. 20 is used in a slightly changed version, where the nominal input flow is replaced with the last recorded input value, u_{t-1}:

$$u(t) = u_{t-1} + K_c\big(y(t) - y_{SP}(t)\big) \qquad \text{eq. (24)}$$

Control loop 2 on the other hand, has the volume of Kalkbrænderihavnsgade pumping pit (V_{KG}) as the controlled variable. Here a standard P-controller is applied. The tuning is done using eq. 21. The closed loop constant is chosen to be 10, corresponding to a gain of 0.2. The nominal input is chosen to be the maximum capacity of the actuator.

For the determination of setpoints, the objective function for the control, eq. 22, is considered together with operational knowledge of the system. It is found that control loop 1 needs to have different setpoints during the different operational modes. This is because the controlled variable is highly influenced by the disturbance and therefore it is necessary to vary the setpoint of the controller, to ensure setpoints are chosen that can be achieved and stable operation is obtained.

The implemented control parameters can be seen in Table 9.

Table 9: Control parameters y_{sp}, $\bar{u}$ and K_c

Manipulated variable / Operational mode	Control loop 1			Control loop 2			Control loop 3		
	y_{sp} [m^3/s]	$\bar{u}$ [m^3/s]	K_c [-]	y_{sp} [m^3]	$\bar{u}$ [m^3/s]	K_c [-]	y_{sp} [m^3/s]	$\bar{u}$ [m^3/s]	K_c [-]
Dry weather	0.17	-	1	-	-	-	-	-	-
Filling	0.9	-	1	-	-	-	-	-	-
Saturation	0.9	-	1	-	-	-	-	-	-
Emptying	0.6	-	1	1280	0.5	0.2	1	-	1

Finally, a deadband is implemented in control loop 1 to avoid chattering, leading to frequent activation and deactivation of the controller during dry weather. If the water level in the pumping pit of P1, V_{KG}, is so low that the pump is in risk of losing the water (the pumping pit is less than 1/10 full), the controller is deactivated and it is only reactivated once the level in the pumping pit is at a higher level (more than 1/3 full).

It should be noted that in the design of the controllers, the rules for switching between the operational modes are based on the states of the individual volumes connected to the manipulated variable. Therefore, at any given point in time, the three manipulated variables can be in different operational modes in the evaluation.

4.5 *Step 5: Evaluate control loops*

The evaluation of the control loops are done as described in section 2.5.

The stability of the control loops are evaluated visually from a plot of the results of a simulation done with a CDS rain (the same as applied in section 4.2). The results are shown in Figure 9.

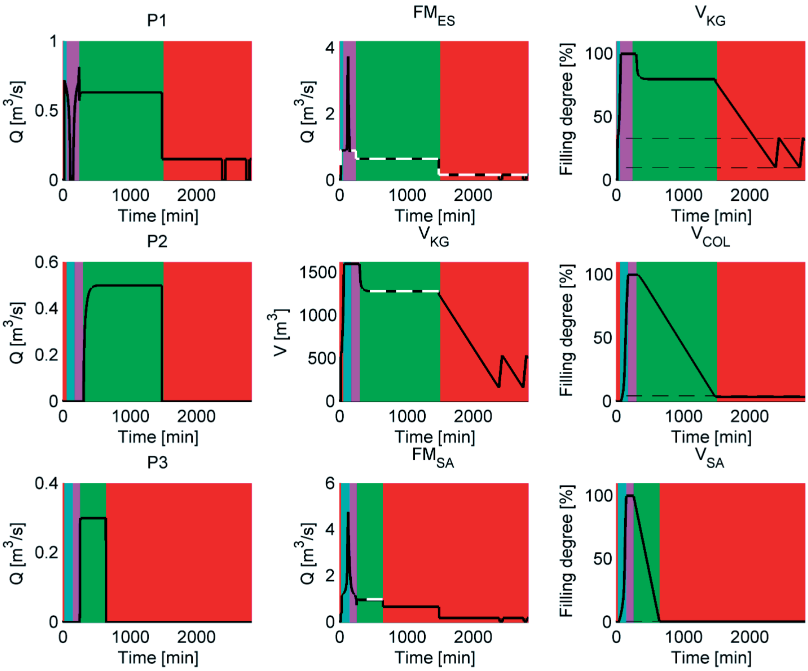

Figure 9: Simulation results showing the three control loops (control loop 1 at the top to control loop 3 at the bottom), with the MV to the left, the CV in the centre and the connected volume to the right. The white dashed lines are the setpoint trajectories and the black lines are the actual trajectories. The background colours represent the different operational modes (red = dry weather, cyan = filling, pink = saturation, green = emptying). The dashed black lines are the activation/deactivation thresholds.

From Figure 9 it can be seen that the controllers provide a stable output response during the filling, saturation and emptying phases and are capable of handling large changes in the disturbances, as they are able to follow the setpoint trajectories. The small variations in the manipulated and controlled variables during the dry weather phase do not affect the overflow and thus do not affect the results of the objective function.

The results also illustrate why control loops 2 and 3 are only active during the emptying phase, as this is the only phase where there is water in the basins and the controlled variables are not saturated at their maximum values.

From Figure 9 it can also be seen that P_1 saturates at the lower limit from time to time during the dry weather phase, which can also be seen from the plot of V_{KG}, where the deadband of control loop 1 is shown. This is due to a higher outflow from the pumping station than inflow. The plots furthermore show how these fluctuations are repeated downstream from P_1, where the CV of both control loop 2 and 3 are affected. Based on the gain matrix this was expected. In the model the fluctuations could have been avoided since the dry weather flow is constant and if the setpoint was chosen to be the value of the dry weather flow, there would be no fluctuation. However, in real life such fluctuations are unavoidable, since the disturbance from the dry weather flow will not be constant and therefore the chosen control law will lead to small fluctuations in the downstream flow during dry weather.

The second part of the evaluation is a comparison between the implemented control structure and an open loop operation of the system. Ten years of historical rain events are simulated with the Matlab model without and with the control implemented (or open and closed loop), and the overflows recorded. The total sum of the overflow is calculated as well as the total CSO for each of the overflow locations (eq. 22 and 23). The results can be seen in Table 10.

Table 10: Accumulated overflow from a simulation with a ten year historical rain series.

	UO17 [m^3]	UO32 [m^3]	UO38 [m^3]	UO42 [m^3]	UO44 [m^3]	TOTAL CSO [m^3]
Open loop	454	22,619	13,693	265	0	17,032
Closed loop	450	4,885	1,764	266	995	8,360

The results in Table 10 show that implementing the control structure reduces the total CSO to less than half. This is achieved by controlling the distribution of water within the basins and by obtaining a shorter emptying time of the basins. Particularly the detention basin Colosseum is utilised much better with the control, resulting in a dramatic reduction in the overflow from UO38, at the expense of a higher overflow from UO32.

The results in Table 10 however also show that not all of the overflows are affected by the implementation of the control. The changes in the CSO from both UO17 and UO42 are negligible. The reason for this is that neither the flows to nor from these two bottlenecks are controlled.

Considering that the objective for the sewer system control was to minimize the total CSO, the implemented control is concluded successful at minimizing the objective function and reducing the effects of disturbances.

5 DISCUSSION AND PERSPECTIVES

A general methodology for regulatory control design is applied to the sewer system. Because the sewer system dynamics are not continuous and the disturbances are transient and large in nature, the methodology has been adapted to be used for sewer system operation.

In this paper it was decided to work in the Laplace domain. This choice was made, because the of the rich classical control toolbox available that offer tools and methods for controllability analysis.

However, in the future, to further facilitate the application of this methodology in practice, an alternative is to obtain the process gain matrix needed for controllability analysis from time-domain models e.g. step-change response analysis (Seborg *et al.* 2011). The disadvantage of this is that it is a quite time consuming task, since it will require many simulations to determine the gain matrices, but it effectively elimininates the need for obtaining the evaluation model in a separate step, and the gain matrices can be obtained while staying in the time domain. This could be considered an advantage by industry, since the traditional methods for analysing the sewer system operation is in the time domain.

For designing the regulatory layer control, in addition to the singular value decomposition (SVD) method used here to determine the CN of many combinations of control loop candidates, one can also alternatively use non-square RGA as well as self-optimising control principles (Mauricio-Iglesias *et al.* submitted). Each method has pros and cons. Self-optimising control needs comprehensive optimisation analysis, as the control and the optimisation are both embedded together in the controller. The opposite apply to the methodology used in this paper. When designing the regulatory control for the control purpose alone, the regulatory control layer requires a separate, higher layer for determining the optimal setpoint values for the operation (Figure 2). For this purpose an optimisation framework of some sort could be used like the framework proposed by Vezzaro and Grum (2014).

In this paper the focus is solely on the design of the regulatory control layer, which is why the results in Table 10 are compared to open-loop dynamics. However, HOFOR has been working with implementing and optimising their control of the sewer system in Copenhagen for more than 10 years and the case study area actually already have a distributed control structure implemented with complex rule based control. It is however the wish of the utility company to investigate if the existing control structure could be exchanged by a more centralised control structure, where the setpoints are determined by an optimisation layer. The benefit of adding an optimisation layer is that it will make it possible to prioritise more easily between different objectives or even just give different weights to the individual overflow locations, such that protecting sensitive receiving waters can be prioritised over the protection of more robust water bodies. Also it possibly allow for a more integrated operation with the wastewater treatment plants and also water quality based control objectives can be considered.

The interaction between the regulatory control layer and an optimisation layer will therefore be the focus of a subsequent research paper.

6 CONCLUSIONS

A methodological approach to designing the regulatory control layer for a sewer system has been presented in this paper.

For the analyses a simplified model of the sewer system that is based on mass balances, was built for control analysis and evaluation purposes. Despite its simplicity the model proved capable of simulating the most important dynamics of the sewer system as compared with a more detailed model based on first principles.

Due to the dynamics of the sewer system not being continuous and the disturbances being transient and large in nature, the methodology had to be adapted to be used for sewer system operation. One means of doing so was to determine the linear model at several different operating points during the simulation of a rain event. Based on the results it was found possible to differentiate between four distinct operational modes (dry weather, filling, saturation and emptying), within which the linear model could be assumed the same for all operating points.

Applying the methodology and the tools for analyses on the case area provided insights on the dynamics of the sewer system and the behaviour of the recirculation loops related to the offline basins that were not evident from the beginning. Based on the analysis of the system a possible control structure for the regulatory control layer was found that was implemented and evaluated successfully. Using a 10 year historical rain series the model was simulated with and without control, and the results show that implementing the control more than halves the total CSO from the system compared to having no control. Future perspectives include evaluation of the regulatory control layer in combination with higher layers in the control hierarchy, such as an optimisation layer.

From the application of the methodology on a small subsystem of the sewer system, it was found that the analyses provided insights on the dynamics of the system and the interactions between the loops that were not evident from the beginning. Also the control structures that were of interest for further investigation were effectively identified, reducing the control degrees of freedom and simplifying the design problem.

With the methodology having proved its value on a small subsystem of the sewer system, by extrapolation the methodology is expected to have great value when analysing larger sewer systems with many actuators and measurements.

7 ACKNOWLEDGEMENT

Thank you to Dr. Miguel Mauricio Iglesias for his invaluable help with Matlab and knowledge on control theory. Also the authors would like to sincerely thank Dr. Niels Bent Johansen for his participation and contribution to inspirational discussions on sewer system control.

This project is initialized and financed by Copenhagen Wastewater Innovation and is financially supported by The Danish Agency for Science, Technology and Innovation under the Industrial PhD program (project number 11-109494). Support was furthermore received from the Danish Council for Strategic Research, Programme Commission on Sustainable Energy and Environment, through the Storm- and Wastewater Informatics (SWI) project (http://www.swi.env.dtu.dk). The support is greatly acknowledged.

8 ADDITIONAL MATERIAL

Additional material can be obtained by contacting the corresponding author of the paper. The additional material includes Matlab scripts and Simulink models (version 2012b) as well as the datasets used in this project.

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APPENDIX A

The parameter estimation for the virtual Tank model is done using eq. 8 and 9, respectively.

As mentioned in section 3 the method used for the parameter estimation is a local optimisation method. The function has a problem with finding the optimum solution, if all parameter values in the neighbourhood of the initial values lead to zero overflows in the model simulation, resulting in the optimisation terminating before the actual optimum solution is found. An initial estimation of the parameter values is therefore done by trial-and-error using a Chicago Design Storm (CDS) rain (Keifer and Chu 1957) obtained from the Danish regional intensity-duration-frequency relationships (Arnbjerg-Nielsen *et al.* 2002; Madsen *et al.* 2009). The CSD is chosen to have a five year return period, the duration of the rain was set to four hours and the shape as symmetrical, resulting in a maximum intensity of 16.74 μm/s.

The choice of return period is made to ensure that CSO's will occur at all the overflow locations. The estimated parameter values are then used as initial guess for the final calibration.

Alternatively a global search algorithm could have been used which requires more evaluations runs, but is less sensitive to the initial starting point.

For the final calibration and validation a 20 year rain series is used (SVK[3] rain gauge 5740). From this rain series rain events with a return period of more than two years are extracted (with respect to the mean 30 minute intensity or the depth). This results in a list of 19 rain events. Of these the first 10 events are used for the calibration and the last 9 are used for the validation.

The results of the parameter estimation can be seen in Table A.1.

[3] The SVK rain gauge network is a nationwide network in Denmark operated by the Danish Water Pollution Committee (in Danish: Spildevandskomiteen; see Jørgensen *et al.* (1998).

Table A.1: Calibrated parameter values.

	β_{VT1}	β_{VT2}	β_{VT3}	β_{VT4}	β_{VT5}	β_{PB}
SE	0.0334	0.0259	0.1312	0.1174	0.4123	0.0370
SSE	0.0334	0.0269	0.1036	0.0955	0.0714	0.0369

From Table A.1 it can be seen that only one of the estimated parameter values (β_{VT5}) is significantly affected by the choice of objective function. Differences in the parameter values are expected to impact mainly the simulations of the overflows with no volume connected to them, as the flows to these structures are not dampened by the retention of the water. The calibration results are plotted in Figure A.1 to A.5.

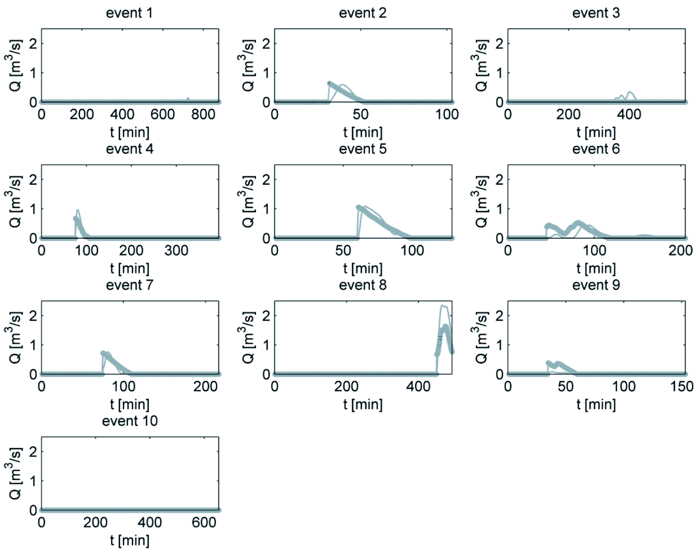

Figure A.1: Calibration results for UO17. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

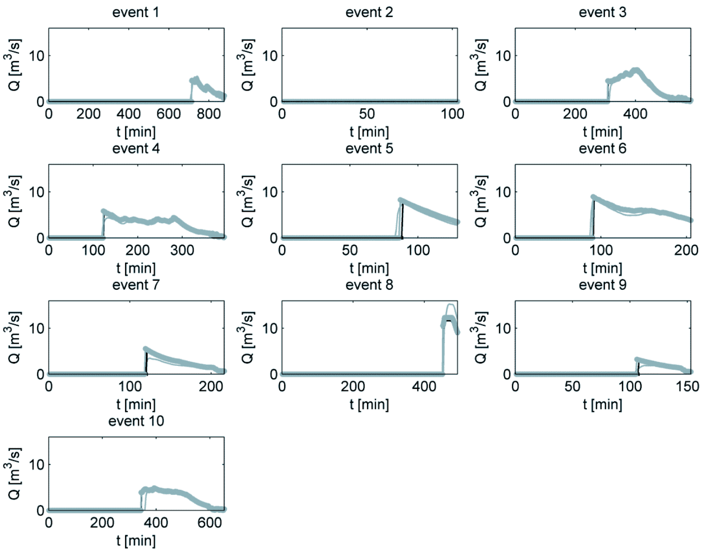

Figure A.2: Calibration results for UO32. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

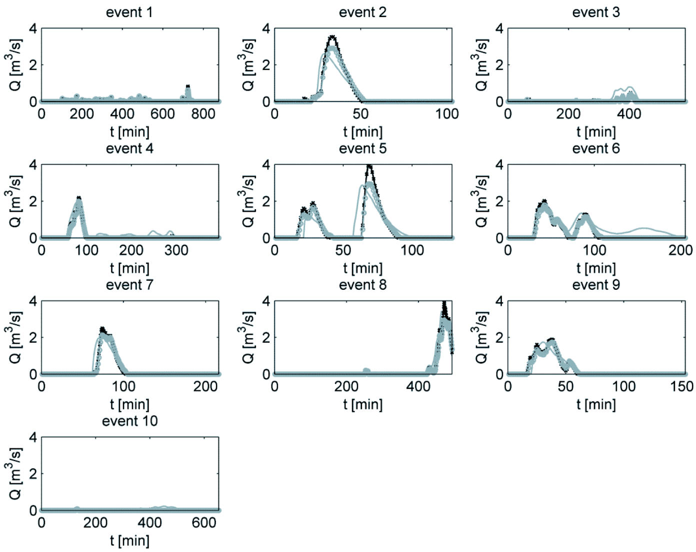

Figure A.3: Calibration results for UO38. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

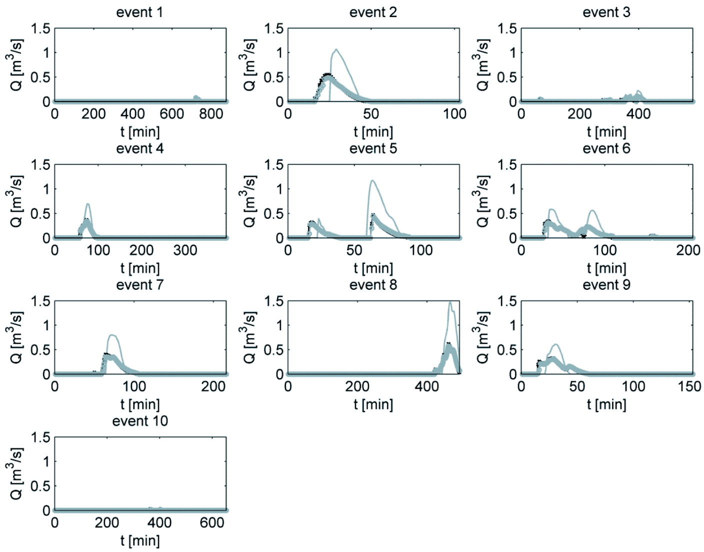

Figure A.4: Calibration results for UO42. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

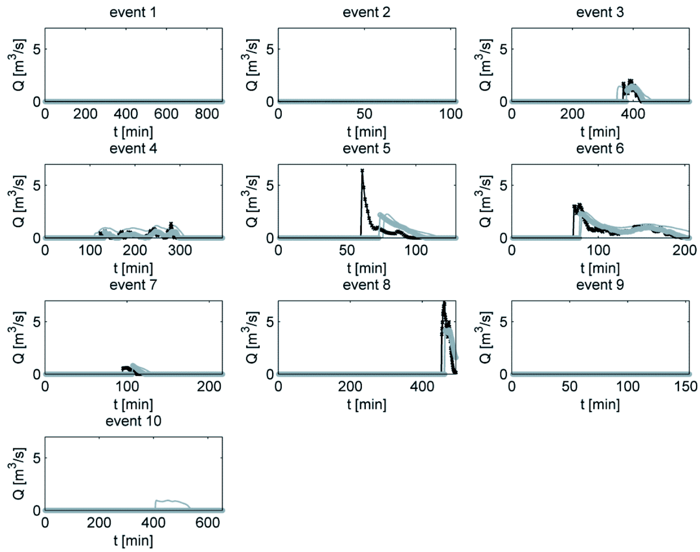

Figure A.510: Calibration results for UO44. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

When looking at the overflow hydrographs in figures A.1 to A.5, it can be seen that the simulations of the overflows have the correct dynamics and that the two parameter sets provide very similar simulation results. In most instances the results are so similar the two curves cannot be distinct from each other.

As expected the simulations of the overflow from UO44, which is highly affected by the parameter value of β_{VT5}, yield slightly different results. However, from the plots it is not possible to visually see, which of the methods provide the best calibration result. The validation is therefore done using both calibrations.

APPENDIX B

In Table B.1 the statistical indicators based on the SE calibration can be seen.

Table B.1: Statistics on the model fit when the parameter estimation is done on overflow volumes (SE).

Parameter	Measurements		No. of observations	MAE	RMSE	J
			[-]	[m^3/s]	[m^3/s]	[-]
β_{VT1}	UO17	Calibration	3806	0.02	0.10	0.96
		Validation	5003	0.01	0.09	
β_{VT2}	UO32	Calibration	3806	0.22	0.68	0.58
		Validation	5003	0.14	0.40	
β_{VT3}	UO38	Calibration	3806	0.08	0.22	0.57
		Validation	5003	0.03	0.13	
β_{VT4}	UO42	Calibration	3806	0.03	0.11	0.57
		Validation	5003	0.01	0.06	
β_{Vt5}	UO44	Calibration	3806	0.15	0.48	0.29
		Validation	5003	0.03	0.14	
β_{PB}	UO17	Calibration	3806	0.02	0.10	0.96
		Validation	5003	0.01	0.09	

The results are plotted in Figures B.1 to B5 below.

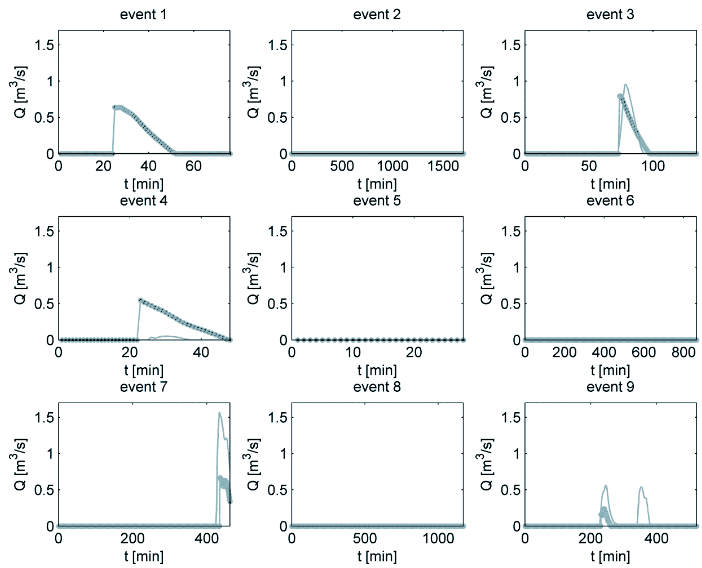

Figure B.1: Validation results for UO17. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

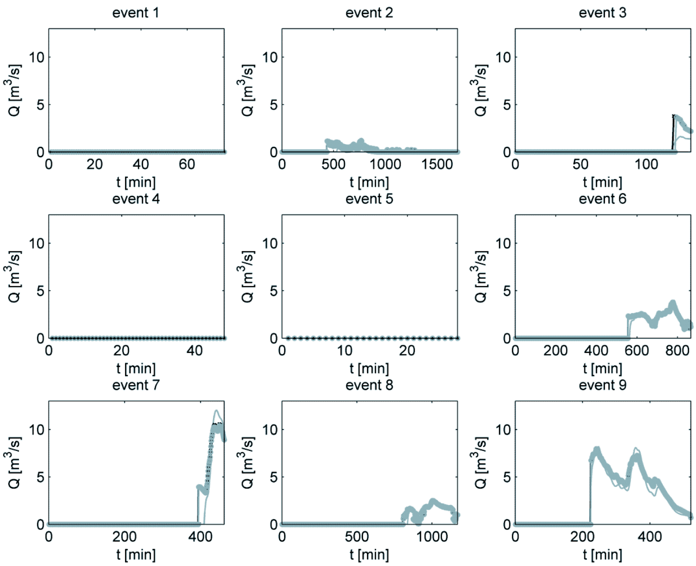

Figure B.2: Validation results for UO32. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

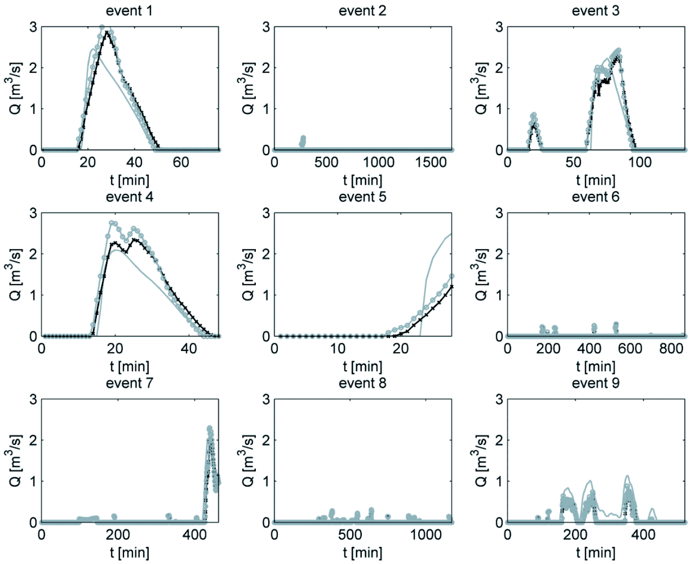

Figure B.3: Validation results for UO38. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

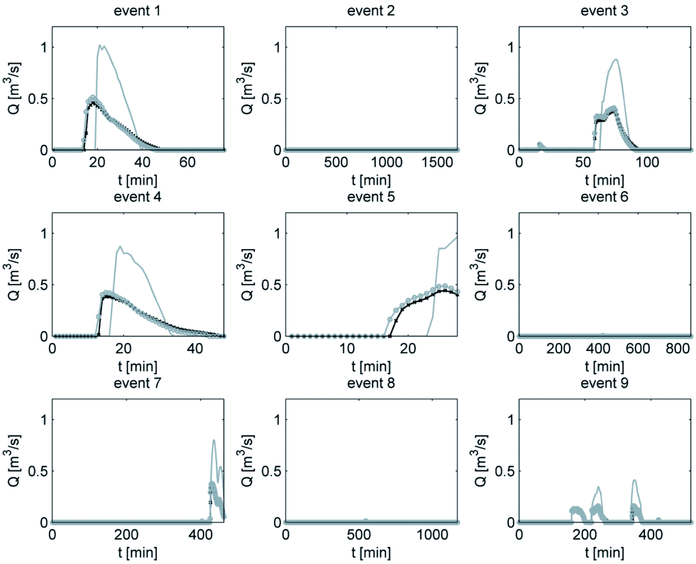

Figure B.4: Validation results for UO42. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

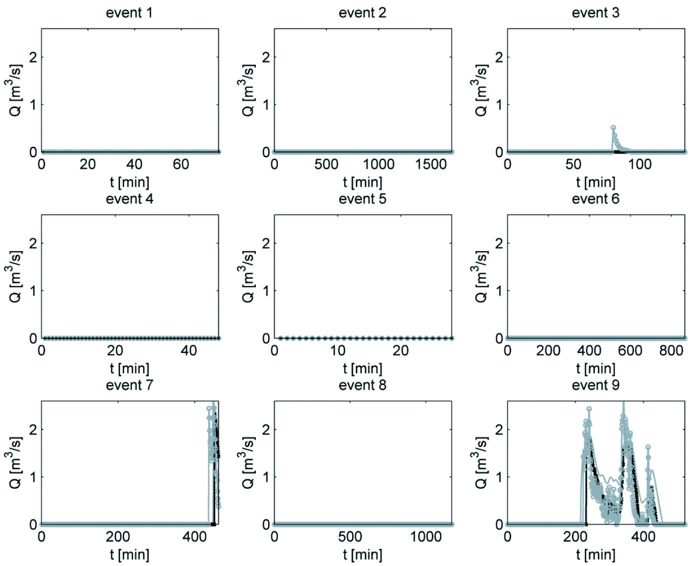

Figure B.5: Validation results for UO44. The solid, grey line is the Mouse model results, the black line with the x-markers is the Virtual Tank model results when calibrated with the SE objective and the grey line with the ring markers is the Virtual Tank model when calibrating with the SSE objective.

APPENDIX C

Table C.1: Gain matrix at a frequency of 0.65 rad/min. After scaling.

	Dry weather (t = 0 - 45)			**Filling** (t = 75 - 165)			**Saturation** (t = 195 - 225)			**Emptying** (t = 465 - 2500)		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
FM_{ES}	0.20	0	0	0.20	0	0	0.20	0	0	0.20	0	0
FM_{AH}	0.62	0	0	0.62	0	0	0.62	0	0	0.62	0	0
FM_{SA}	0.18	0	0.06	0.18	0	0.06	0.18	0	0.06	0.18	0	0.06
UO32	0	0	0	0	0	0	-0.21	3 e-12	0	0	0	0
V_{COL}	0	-0.001	0	-0.002	-4 e-13	0	0	0	0	0	-0.001	0
IO_{KG}	0	0	0	-0.09	0.05	0	-0.09	0.05	0	0	0	0
V_{KG}	-0.05	0.03	0	0	0	0	0	0	0	-0.05	0.03	0
UO_{17}	0	0	0	0	0	0	0	0	0	0	0	0
UO_{44}	0	0	0	0	0	0	0	0	0	0	0	0
V_{SA}	0	0	-0.004	0	0	-0.004	0	0	0	0	0	-0.004
UO_{38}	0	0	0	0	0	0	0	0	0	0	0	0
UO_{42}	0	0	0	0	0	0	0	0	0	0	0	0
FM_{out}	0.90	0	0.30	0.90	0	0.30	0.90	0	0.30	0.90	0	0.30

III

A methodological approach to the design of optimisation and control strategies for sewer systems

Ane Loft Mollerup, Peter Steen Mikkelsen, Dines Thornberg and Gürkan Sin

A methodological approach to the design of optimisation and control strategies for sewer systems

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ABSTRACT

This study first focuses on designing an optimisation based control for sewer system and secondly linking it to a regulatory control (previously designed in (Mollerup *et al.* 2015)). It is investigated how the choices made when designing the optimisation, affect the results of the control system. A benchmarking of the performance is made between the regulatory control and the new optimising control (where the optimisation acts directly on the actuators) and the optimisation coupled with regulatory control.

The results reveal only small differences in the performance of minimising overflow volume. This suggests that for small sewer systems, like this case study, regulatory control can be as effective a strategy as the more advanced optimisation strategies. Hence, for the design of sewer system control, it is important to systematically test from simpler to more advanced strategies.

Keywords: Sewer system control; methodology, optimisation; regulatory control, benchmarking, control hierarchy

Abbreviations: Chicago design storm (CDS), Combined sewer overflow (CSO), controlled variable (CV), manipulated variable (MV), planning aid for sewer system real time control (PASST), proportional controller (P-controller), proportional integral derivative (PID), root mean square error (RMSE), Single-Input Single Output (SISO), The Water Pollution Committee of The Society of Danish Engineers (in Danish: Spildevandskomiteen) (SVK), virtual tank (VT).

1 INTRODUCTION

When planning a new structure in the sewer system, methods and tools are available that facilitates the design process. However, similar tools and methods are missing for the design of control systems. A methodology exists to determine if there is a potential for control (PASST[1]) (Schütze *et al.* 2004a), but this does not cover how to actually design a control system. For this process urban drainage planners rely on operational knowledge combined with model simulations and trial and error.

Control can be used to adjust for the uneven distribution of available transport and storage capacity by redirecting or retaining water during rain events, and thereby improve the performance of the existing structures (Schütze *et al.* 2004b). A controller works by adjusting the actuator to meet the defined setpoint, however in sewer systems the range of flows is often so large that controllers with static setpoints will not operate in an optimal way. Instead the setpoints needs to change according to the state of the system. One way of determining the setpoints is from an online optimisation. A general approach to designing an optimisation has been suggested by Seborg et al. (2011). This is shown in Figure 1, where it is linked to the time dependent control hierarchy for sewer systems (Mollerup *et al.* submitted).

The design of the regulatory control layer was the subject of a previous paper (Mollerup *et al.* 2015). In this paper the focus is first on designing an optimisation and second on linking the optimisation to the regulatory control layer. This paper will investigate, how the choices made when designing the optimisation, affect the results of the control system. A benchmarking of the performance is then made between the existing control, the regulatory control (Mollerup et al., 2015), the new optimising control (where the optimisation acts directly on the actuators) and the new hierarchical control (where the optimisation acts on the regulatory control layer through the exchange of setpoints).

[1] Planning aid for sewer system real time control

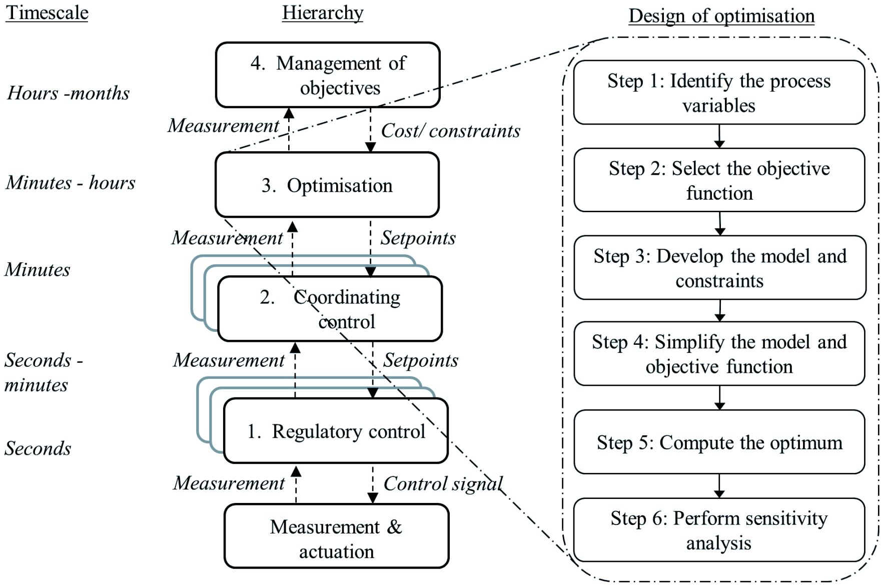

Figure 1: Methodology for designing an optimisation (based on Mollerup *et al*. submitted and adopted from Seborg 2010)).

The paper is structured in the following way: First an outline of the methods and tools used in the paper is given. Next the methodology is applied to the case study, using a simplified model of the sewer system. The case study is used to evaluate the influence on the performance from the design degrees of freedom at each step. The optimisation is coupled with a regulatory control layer and the performance of the different control system configurations are evaluated from model simulations. Finally the results are discussed and conclusions drawn.

2 DESIGNING AN OPTIMISATION – METHODS AND TOOLS

The optimisation problem can be generically formulated as follows:

$$\underset{u}{\operatorname{argmin}} \int_{t}^{t+\Delta t} F(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d}) \qquad \text{eq. (1)}$$

subject to

$$\frac{d\boldsymbol{x}}{d\boldsymbol{t}} = h(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d}) \qquad \text{eq. (2)}$$

$$\boldsymbol{y} = g(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d}) \qquad \text{eq. (3)}$$

$$\boldsymbol{x}_{min} \leq \boldsymbol{x}_t \leq \boldsymbol{x}_{max} \qquad \text{eq. (4)}$$

$$\boldsymbol{u}_{min} \leq \boldsymbol{u}_t \leq \boldsymbol{u}_{max} \qquad \text{eq. (5)}$$

$$\boldsymbol{y}_{min} \leq \boldsymbol{y}_t \leq \boldsymbol{y}_{max} \qquad \text{eq. (6)}$$

where $F(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d})$ is the objective function for the optimisation, $h(\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}, \boldsymbol{d})$ is the model of the system, $\boldsymbol{u}$ are the inputs or manipulated variables (MV), $\boldsymbol{x}$ are the states, t is time, Δt is the control horizon used, $\boldsymbol{d}$ are the disturbances and $\boldsymbol{y}$ are the model outputs or the controlled variables (CV). The indexes *min* and *max* indicate the lower and upper constraints.

In Figure 2 the different time horizons used in online optimisation and the interrelationship between them are illustrated (from Rauch and Harremöes 1999). As indicated in Figure 2 the prediction horizon is the time it takes, before all effects have been accomplished. In a sewer system that is the retention time of the system, when focusing on CSO. The forecast horizon is the period where all the inputs are known. The control horizon is the simulation time of the optimisation and the sampling time is the time between recalculation of the optimisation and is denoted T_s.

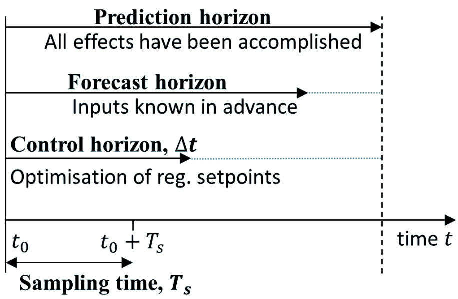

Figure 2: Schematics of time horizons applied in optimisation (from Rauch and Harremöes, 1999).

4

As mentioned in the introduction a general approach for optimisation design is followed. However, as the design of the regulatory control layer was the subject of a previous paper, the three first steps have already been addressed. The methodology is therefore adapted accordingly and is illustrated in Figure 3.

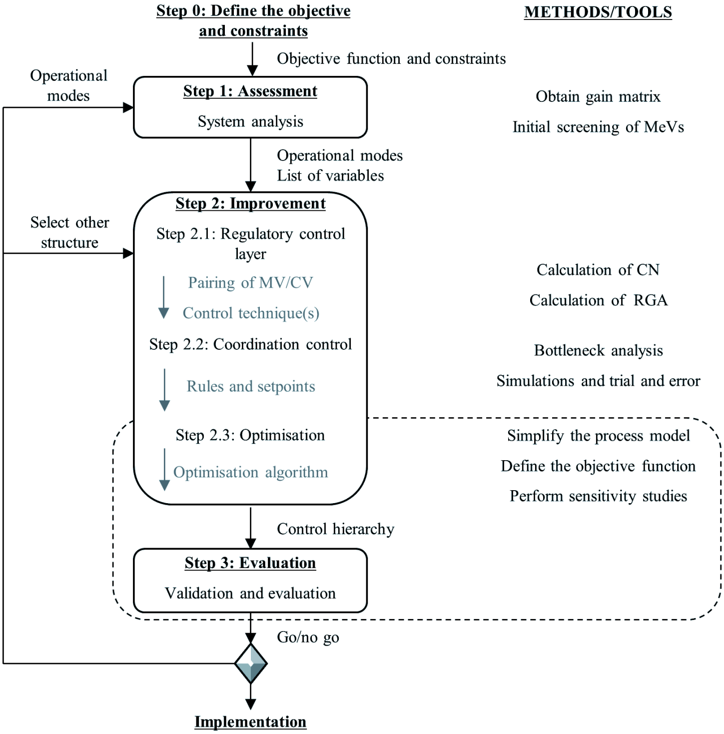

Figure 3: Methodology. The dashed line circles the steps addressed in this paper.

Each of the steps 2.3 and 3 from Figure 3 is described in the following.

2.1 Simplify the process model

When solving an optimisation the computational time is related to the model size and complexity. In this step the evaluation model is therefore simplified to different degrees and benchmarked against each other. The benchmarking parameters are chosen to be the root mean square error (RMSE) and computational time.

$$\mathrm{RMSE} = \sqrt{\frac{1}{J}\sum_{j=1}^{J}\left(\hat{\boldsymbol{y}}_j - \boldsymbol{y}_j\right)^2} \qquad \text{eq. (7)}$$

where J is the number of observations, $\hat{y}_j$ are the simulation results of the process model and y_j are the simulation results of the evaluation model.

The model evaluation is performed with a Chicago design storm (CDS) (Keifer and Chu 1975).

2.2 Define objective function

An overall objective for sewer system control was defined in Mollerup *et al.* (2015) as minimizing the CSO volume. However, translating this to a mathematical problem to be solved by the optimisation can be done in different ways (Schütze *et al.* 2004b, Fiorelli *et al.* 2013). The following are investigated in this paper:

1) Minimise the CSO volume:

$$F_1 = \sum_{h=1}^{H}\sum_{j=1}^{J}\boldsymbol{UO}_{h,j} \qquad \text{eq. (8)}$$

where H is the number of external overflow structures and $\boldsymbol{UO}_{h,j}$ are the external overflow observations.

2) Use as much of the storage capacity as possible by ensuring an even filling degree:

$$F_2 = \sum_{k=1}^{K}\mathrm{abs}\left(fd_{ev} - \frac{x_k}{x_{k,max}}\right) \qquad \text{eq. (9)}$$

where x_k is the volume of water in the basins, K is the number of basins, $x_{k,max}$ is the storage capacity and fd_{ev} is the even filling degree, which is calculated from:

$$fd_{ev} = \frac{\sum_{k=1}^{K} x_k}{\sum_{k=1}^{K} x_{k,max}}$$

3) Maximize the flow to the treatment plant:

$$F_3 = \sum_{l=1}^{L} \mathrm{abs}(y_l - y_{l,max}) \qquad \text{eq. (10)}$$

where y_l is the flow at the bottleneck, $y_{l,max}$ is the maximum capacity at the bottleneck and L is the number of bottlenecks in the system.

A different objective related to the operation of the actuators is to minimise fluctuations. This can be done by penalising the change in the inputs. Here it is chosen to penalise the deviation in the CV from a predetermined volume of water in the tank:

$$F_4 = z - z_{SP} \qquad \text{eq. (11)}$$

where z_{SP} is the desired volume in the tank to be kept and z is the actual volume.

Finally the objective function can be formulated as a sequence of objectives being weighted and summarised:

$$F = \sum_{m=1}^{M} w_m \times F_m / F_{m,max} \qquad \text{eq. (12)}$$

where M is the number of terms included in the final objective function, w_m is the weighting factor for de individual terms, F_m is the objective function term and $F_{m,max}$ is the maximum range of the objective function output.

The objective functions are compared based on the same CDS rain as used for the process model evaluation (section 2.1). The sampling time and the control horizon are selected based on the transportation lag-time in the system. The optimisation algorithm is chosen to be a constrained nonlinear optimisation method already embedded in Matlab (*fmincon*). This is used for all subsequent optimisation simulations.

2.3 Perform sensitivity studies

If the optimisation model is ill-defined, this will of course be reflected in the optimisation results. Therefore a sensitivity analysis and tuning is performed, to identify if the optimisation problem and its solution can be further improved.

The degrees of freedom investigated in the sensitivity analysis are the weighting factors used in the objective function formulation (w-values). A local sensitivity analyses is performed:

$$S_1 = \frac{\partial F}{\partial \theta_n} \qquad \text{eq. (13)}$$

where F is the objective function and θ_n are the parameters to be investigated. Large values of S indicate that the objective function is sensitive to changes in the parameter. A negative value indicates a better performance, while a positive value indicates the opposite.

A coupled rain event should be used in the analysis to make certain that the objective function formulation can handle coupled events.

Apart from the traditional sensitivity analysis, a tuning of the control horizon (Δt) together with the sampling time (T_s) is also performed. The two parameters are linked as shown in Figure 2, page 4. The tuning is done from simulating a number of scenarios and comparing them based on the objective function). For the control horizon, a lower and upper bound is defined around the nominal value used in the objective function evaluation (section 3.3). For the lower bound a value less than the transportation lag-time in the system should be chosen, as its effect is interesting to observe. For setting an upper bound the approximated first order time constant of the system is used. The time constant of the system can be approximated as follows: The shortest emptying time of the sewer basins is determined. To this time constant half of the transportation lag-time related to the actuator in that basin is added (Seborg et al. 2011). Choosing the control horizon to be less than the time constant of the system will ensure that the controller can act faster than the system dynamics. The sampling time is selected to be the same as the optimization/control horizon.

The scenarios are run with the previously chosen CDS rain (used in sections 2.1) as well as a historical rain event with a similar return period.

2.4 Evaluation

Based on the results of the previous sections the optimisation problem is defined. The optimisation is evaluated against the current performance of the sewer system as well as other potential control system solutions.

The benchmarking parameters are chosen to be the total sum of CSO (eq. 8) as well as the sum of the overflow at each of the overflow locations:

$$\boldsymbol{UO_h} = \sum_{j=1}^{J} \boldsymbol{UO}_{h,j} \qquad \text{eq. (14)}$$

where $\boldsymbol{UO}_{h,j}$ are the external overflow observations, J is the number of observations, and h represents the different overflow locations.

The evaluation is done with a one year historical rain series.

3 CASE STUDY

A small, but representative case study was selected to motivate and highlight the application of the methodology to sewer systems. In this section the main findings of the study are shown.

3.1 Case study description

The case area is a sub catchment of Copenhagen's sewer system owned and maintained by HOFOR[2]. It has a size of 320 hectare (impermeable area) and is equipped with three pumping stations, two storage tanks, one pipe basin and five CSO structures (see Figure 4). The disturbances to the system are the sewerage (dry weather flow) and the rainfall runoff.

[2] Danish: Hovedstadsomårdets Forsyningsselskab, English: Copenhagens Utility Company. www.hofor.dk.

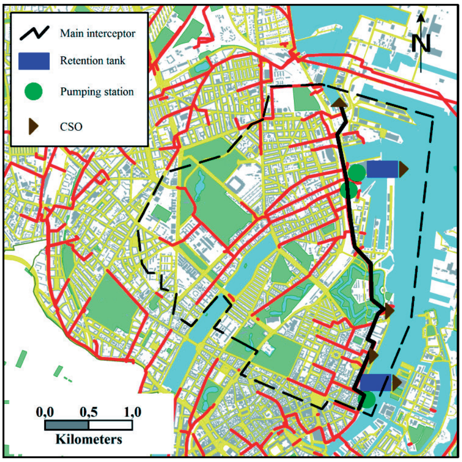

Figure 4: Case area.

A virtual tank (VT) model (Ocampo-Martinez 2010) of the system was presented in Mollerup *et al.* (2015). The VT model is a simple mass balance model using ordinary differential equations (ODE) to describe the temporal change in volumes. The VT model of the case study in state space form can be written as:

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{Ax} + \boldsymbol{Bu} \qquad \text{eq. (15)}$$

$$\boldsymbol{y} = \boldsymbol{Cx} + \boldsymbol{Du} \qquad \text{eq. (16)}$$

where $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$ are matrices, $\boldsymbol{x}$ are the states, $\boldsymbol{u}$ are the inputs and $\boldsymbol{y}$ are the outputs.

Figure 5 shows a schematic representation of the case study model implemented in Matlab/Simulink. The relationship between the states, inputs and outputs of the VT model and the symbols used in Figure 5 is shown in Table 1.

Table 1: The states, inputs and outputs of the state-space model (the names of the variables correspond to those used in Figure 5).

i	1	2	3	4	5	6	7	8	9	10	11	12	13
x_i	V_{KG}	V_{COL}	V_{SA}										
u_i	P1	P2	P3										
y_i	FM_{ES}	FM_{AH}	FM_{SA}	FM_{out}	IO_{KG}	V_{KG}	V_{COL}	V_{SA}	UO17	UO32	UO38	UO42	UO44

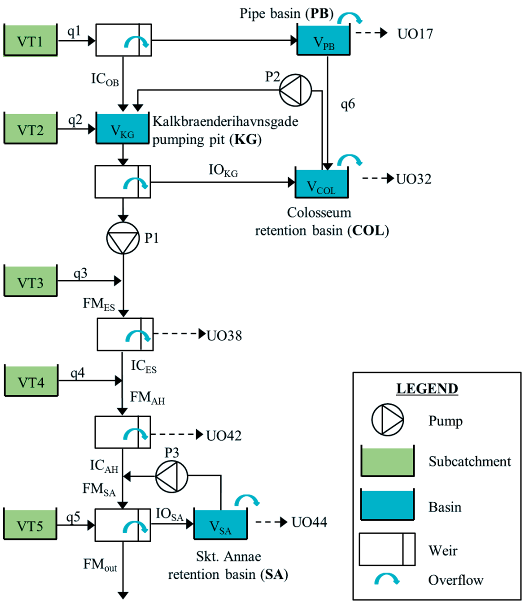

Figure 5: *Schematic representation of the virtual tank model of the case study area. The abbreviations used are: VT = Virtual tank, P = pumping station, UO = External overflow, IO = Internal overflow, FM = Flow measurement, IC = Interceptor.*

In The case study is a small part of the sewer system in Copenhagen. It is therefore assumed that rainfall fall homogenously over the whole catchment. The time of concentration in the system is mainly related to the runoff routing. However there is also a significant transportation time from Kalkbrænderihavnsgade Pumping Station (P1) to Esplanaden (IC_{ES}), which is around 10 minutes.

Table 2 some key characteristics of the case study are shown. It should be noted that there is a significant volume in the pumping pit of KG. It is therefore treated as a basin.

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Table 2: Key characteristics of the case study

Subcatchments	**VT1**	**VT2**	**VT3**	**VT4**	**VT5**
Area [ha]	23.5	222.5	30.0	8.2	33
Dry weather flow [l/s]	29	1035	178	200	2
Retention basins	**PB**	**KG**	**COL**	**SA**	
Volume [1000 m^3]	0.61	1.60	35.72	7.05	
Interceptor pipes	**IC_{OB}**	**IC_{ES}**	**IC_{AH}**	**FM_{out}**	
Full running capacity [l/s]	400	900	1000	1000	
Pumps	**P1**	**P2**	**P3**		
Maximum capacity [l/s]	900	500	300		

3.1.1 Existing control

The existing control uses rules to adjust for the changing conditions of the sewer system (from internal documents describing the controls in HOFOR). They have been finely tuned over time by the operators and urban drainage planners as experiences with the operation have been gained. The outputs of the pumping stations are changed according to the different water levels in the system, in an effort to minimize CSO. The pumping stations emptying the two basins, P2 and P3, are activated based on the level of water in the respective basins and their downstream water levels.

The last pumping station (P1) elevates the wastewater, so it can continue to run by gravitation towards the WWTP. The pumping station has a rule-based control, where measurements downstream as well as local measurements are used. The control technique used at P1 is a proportional integral derivative (PID) controller that aims at keeping the water level in the pumping station fixed. The PID control is combined with a selective control mechanism, constraining the outflow from the pumping station. This has been done to ensure that the flow from the pumping station does not exceed the downstream capacity. The selector chooses the minimum value of the output from the PID controller and three alternatives. All three alternatives are based on downstream conditions. The first two seek to limit the flow to the CSO structure at Esplanaden (FM_{ES}), to minimize the risk of overflow from UO38, based on level measurements at or close to Esplanaden. The last alternative value sent to the selector, comes from the retention basin P1. Therefore, there is known to be a limited capacity of this interceptor pipe during the emptying of V_{SA}. When modelling the controller of P1, a simple P-controller has been implemented. The limitation on the output, due to the downstream conditions at Esplanaden, is modelled using a 1-D look-up table that define the relationship between the flow at FM_{ES} and the maximum allowed flow from P1. The limitation on the output of P1 from $V_{SA,}$ is modelled using rules that evaluate the operational mode of the V_{SA}. During the emptying mode of V_{SA}, P1 is restricted to 1/3 to 2/3 of its full capacity, depending on the level of water in V_{SA}.

3.1.2 Regulatory control

In Mollerup *et al.* (2015) an alternative control system was designed, including the pairing of MVs and CVs and choice of control technique. The pairings of MVs and CVs and the parameters of the controllers are shown in Table 3. Control loops one and three have flows as both the controlled and the manipulated variable. Because of the transient nature of the disturbances, it is not possible to select a nominal input, $\bar{u}$, that leads to a stable proportional controller (P-controller) for these loops. Instead slightly changed P-controllers are used, where the nominal input flow is replaced with the last recorded input value, u_{t-1}:

$$u(t) = u_{t-1} + K_c\big(y(t) - y_{SP}(t)\big) \qquad \text{eq. (17)}$$

where u is the MV, K_c is the controller gain, t is time, $y(t)$ is the CV and y_{SP} is the setpoint.

The setpoints were determined from operational knowledge together with simulations and trial and error. The setpoint for control loop 1 change according to the operational modes of the system: dry weather, filling, saturation or emptying.

Control loop 2 has V_{KG} as the controlled variable. Here a standard P-controller is applied, with a controller gain of 0.2. The nominal input is chosen to be the maximum capacity of the actuator.

Table 3: The parameters of the three controllers (Mollerup *et al.* 2015).

Operational mode	**Control loop 1:** $\mathrm{P1-FM_{Es}}$			**Control loop 2:** $\mathrm{P2-V_{KG}}$			**Control loop 3:** $\mathrm{P3-FM_{SA}}$		
	$\boldsymbol{y_{sp}}$ [m^3/s]	$\boldsymbol{\bar{u}}$ [m^3/s]	$\boldsymbol{K_c}$ [-]	$\boldsymbol{y_{sp}}$ [m^3]	$\boldsymbol{\bar{u}}$ [m^3/s]	$\boldsymbol{K_c}$ [-]	$\boldsymbol{y_{sp}}$ [m^3/s]	$\boldsymbol{\bar{u}}$ [m^3/s]	$\boldsymbol{K_c}$ [-]
Dry weather	0.17	u_{t-1}	1	-	-	-	-	-	-
Filling	0.9	u_{t-1}	1	-	-	-	-	-	-
Saturation	0.9	u_{t-1}	1	-	-	-	-	-	-
Emptying	0.6	u_{t-1}	1	1280	0.5	0.2	1.0	u_{t-1}	1

3.2 Simplify the process model

The VT model can potentially be used as both the evaluation model for benchmarking and the process model for the optimisation. However, the process model has to have both a good performance, meaning it has to be able to predict the future states of the system, and be solved within the sampling time of the optimisation. Three alternative process models are tested and compared to the full process model (VT model). Some characteristics of the models are shown in Table 4.

Table 4: Optimisation model characteristics.

Model	**Modelling software**	**Estimated disturbances**	**Rainfall prediction**	**Forecast**
1	Matlab	q3, q5, $\mathrm{IC_{AH}}$*	No	Constant from measurements
2	Matlab/Simulink	All	Yes	Mean of the previous period
3	Matlab/Simulink	q1-q5, q6, $\mathrm{IC_{OB}}$*	Yes	Actual future rain (perfect information)
VT	Matlab/Simulink	All	Yes	Actual future rain (perfect information)

* See Figure 5, page 11.

The trajectories for the actuators are set from the evaluation model, since no control is yet applied. To make the performance of the model clear, no uncertainty is included in the simulations and the process model states are updated directly from the evaluation model. In any practical application the uncertainty and noise should be considered in the forecast and the model updating. However, these issues are kept outside the scope of this study and therefore the reader is referred to other relevant research (e.g Grum *et al.* 2012, Vezzaro *et al.* 2013, Joseph-Durant *et al.* 2014, Madsen *et al*, 2014, Borup *et al.* 2015).

The simplified models are described below.

3.2.1 Model 1

Model 1 is the simplest model possible. No forecast is available; instead the most significant flows in the sewer system affected by disturbances are assumed measured at the beginning of each optimisation period. The measured flows are assumed constant over the control horizon. Based on these measurements the inflows to V_{KG}, V_{COL} and V_{SA} are estimated along with the CVs (FM_{ES}, V_{KG} and FM_{SA}), using the equations below.

$$V_{KG}(t_0 + \Delta t) = V_{KG}(t_0) - P_1(t) \times \Delta t + P_2(t) \times \Delta t \qquad \text{eq. (18)}$$

$$V_{COL}(t_0 + \Delta t) = V_{COL}(t_0) - P_2(t) \times \Delta t \qquad \text{eq. (19)}$$

$$V_{SA}(t_0 + \Delta t) = V_{SA}(t_0) - P_3(t) \times \Delta t \qquad \text{eq. (20)}$$

$$FM_{ES}(t_0 + \Delta t) = P_1(t) + q_3 \qquad \text{eq. (21)}$$

$$FM_{SA}(t_0 + \Delta t) = P_3(t) + q_5 + IC_{AH} \qquad \text{eq. (22)}$$

, where q_3, q_5 and IC_{AH} are flows know from measurements, *t* is time, t_0 is the starting time of the optimisation period and Δt is the control horizon of the optimisation.

3.2.2 Model 2

In model 2 the VT model is used as the process model. The disturbances are estimated from simulation a rainfall prediction. The rainfall intensity, D_{rain}, is assumed constant and the same as the average rainfall intensity over the last control horizon:

$$D_{rain}(t = [t_0; t_0 + \Delta t]) = \left(\sum_{i=t_0-\Delta t}^{t_0} d_{rain,i} \right) \times 1/\Delta t \qquad \text{eq. (23)}$$

, where d_{rain} is the rainfall intensity observations, t is time and t_0 is the time of the initialisation of the optimisation.

3.2.3 Model 3

Model 3 is split in two as illustrated in Figure 6; a model of the rainfall runoff in Simulink and a model of the sewer system itself in Matlab, which is the model used in the optimisation.

Figure 6: Process model 3. d_{rain} is the forecasted rainfall and q_i are the flows from the sub catchments.

The forecast of the rainfall over the control horizon is assumed known from radar forecasts (perfect forecast) and the VT model is used to predict the future runoff and the flows from the individual sub catchments. This is then fed into a simple mass balance model, slightly extended from Model 1, as calculations of the internal overflows (IO_{KG} and IO_{SA}) are included (to see the full set of model equation please see the supplementary material).

3.2.4 Comparison of process models

Benchmark simulations are run using a CDS rain with a return period of two years[3]. The return period is chosen to be between the known return period for the overflows, which is approximately ½ year, and the return period for surface flooding, which is ten years. The simulations are performed with a sampling time of both five and 30 minutes.

The model dynamics are benchmarked against the evaluations model and each other with respect to the CVs (FM_{ES}, V_{KG} and FM_{SA}), using eq. 7; also the simulation times are recorded[4]. The results are shown in Table 5.

Table 5: Comparison of potential process models to be used in the optimisation problem.

	RMSE [-]		Computational time [s]	
Sampling time	**5 min**	**30 min**	**5 min**	**30 min**
Model 1	39.44	264.18	0.288	0.260
Model 2	10.88	55.12	14.762	5.610
Model 3	3.67	4.40	12.626	3.133
VT model	0	0	22.590	7.259

The results in Table 5 clearly show the choice one has to make, when choosing the model for optimisation. The VT model is the slowest model, but also the most detailed model and therefore has the best fit. All four models have short computational times, since they are all very simple and the case area is small. However, the results show that:

- Going from a model implemented entirely in Matlab (Model 1), to the VT model implemented in Matlab/Simulink (Model 2, 3 and 4) has a significant effect on the computational time, simply because it takes time to repeatedly initialise and run an ODE model.

[3] The CDS rain is obtained from the Danish regional intensity-duration-frequency relationships (Arnbjerg-Nielsen *et al.* 2002; Madsen *et al.* 2009). The duration of the rain was set to four hours, the mean annual precipitation to 640 mm and the shape as symmetrical, resulting in a maximum intensity of 12.64 μm/s and a total rain depth of 23 mm.

[4] The simulations are performed on a HP PC with Intel® Core™ i7-2600 CPU @ 3.40GHz in Matlab 2013a.

- The computational time can be kept down, while still maintaining an acceptable fit, if the rainfall prediction is done separately and then fed to the optimisation as an input as done in Model 3.
- With no rainfall forecast, a model with frequent sampling time will perform reasonable, as even Model 1 with a two minute update has a RMSE of 13.08 and a computational time of 0.263 s.

Testing different models for the optimisation showed that the focus needs to be on both the computational time as well as the needed level of detail, which are contradictory requirements. There is no easy solution to this problem, but researchers are active in this field and different solutions are already implemented and being tested (e.g. Van Nooijen *et al.* 2011, Joseph-Durant *et al.* 2013, Vezzaro *et al.* 2013).

For all subsequent analyses the VT model is used as both the process and the evaluation model as this is the option with the lowest RMSE and the computational time was affordable for the case study under consideration.

3.3 Define the objective function formulation

Each of the equations 8-10 are tested as possible objective functions (F_1 to F_3) as well as combinations of them together with eq. 11 (F_4), through the use of eq. 12. Adding F_4 introduces a penalty, if the volume in V_{KG} deviates from a predefined value; here chosen to be 90 % of the full volume. In the multi-objective function formulation, the two terms are initially weighted the same. The objective functions are compared from simulation results using the same CDS rain as used for the process model evaluation (section 3.2.4). The sampling time and the control horizon are selected to be 15 minutes, to account for the transportation lag-time in the system.

The resulting CSO volumes are shown with a focus on UO32 and UO38, since these two overflows are the only ones affected by the control in this evaluation. The results can be seen in Table 6.

Table 6: Simulation results with different objective function formulations.

Obj. function	$UO32$ [m³]	$UO38$ [m³]	Total [m³]	Advantage (adv.)/Disadvantage (disadv.)
F_1	74	33	115	Adv: It minimizes the overflows directly, making it also possible to prioritize between the different overflows through the use of weights. Disadv: There is nothing driving the emptying of the basins, if no CSO is predicted.
F_2	58	68	134	Adv: It does not require a forecast to yield good results. It is possible to penalise the CSO from basins individually, and thereby prioritize to protect for example sensitive receiving waters. This is done successfully by Van Nooijen *et al.* (2011). Disadv: The objective function has the unwanted effect that when the majority of tanks are full, then the tanks will not empty. Fiorelli *et al.* (2013) also found that it is not suited if the retention tanks have very different emptying time.
F_3	52	33	92	Adv: It only requires a forecast with the length of the longest retention time between any pair of MV and CV. Disadv: It is not possible to penalise the discharge at each CSO.
$F_5 = 1F_1 + 1F_4$*	74	34	115	Adv: Same as for F_1, but at the same time the volume in KG is kept constant during the emptying of COL.
$F_6 = 1F_3 + 1F_4$**	52	33	92	Adv: Same as for F_3, but at the same time the volume in KG is kept constant during the emptying of COL.

* F_1 is scaled by the maximum recorded overflow within the timespan of the control horizon, in the simulation of F_1 alone (25 m³). F_4 is scaled by the maximum deviation from the desired fixed volume (90 % of the volume of VKG equals 1440 m³).

* F_3 is scaled by the maximum capacities of the bottlenecks (900 l/s and 1000 l/s, respectively), F_4 is scaled by the maximum deviation from the desired fixed volume (90 % of the volume of V_{KG} equals 1440 m³).

From the results in Table 6 and Figure 7 it can be seen that:

- Formulating the objective function as a direct minimisation of the CSO, F_1, is not necessarily the best option. The problem with this objective function formulation is that it is only relevant when overflow is predicted or occurring.
- The alternative of using even filling degree, F_2, has the problem that when the majority of the tanks are full, there is nothing driving the emptying of the basins.
- F_3, where the focus is on maximising the amount of treated wastewater, performed well with respect to minimizing the CSO. However, an unwanted interaction between the actuators occurred, resulting in fluctuations in the flow (see Figure 7). This was due to an upstream-

downstream causality caused by large differences in pump capacities and the size of the volumes. The large, offline retention basin, V_{COL}, is emptied very slowly (by P2) down to the pumping pit of P1. However, the pumping pit of P1 (V_{KG}) is by comparison very small, and therefore empties very quickly.

- The problems of F_3 are solved by using a multi-objective function, F_6. In this objective function formulation deviations from a predetermined water level in V_{KG} are penalised, without having a negative influence on the amount of CSO. From Figure 7 it can even be seen that imposing the penalty leads to a faster emptying of V_{COL}, which reduces the risk of overflow due to coupled rain events.

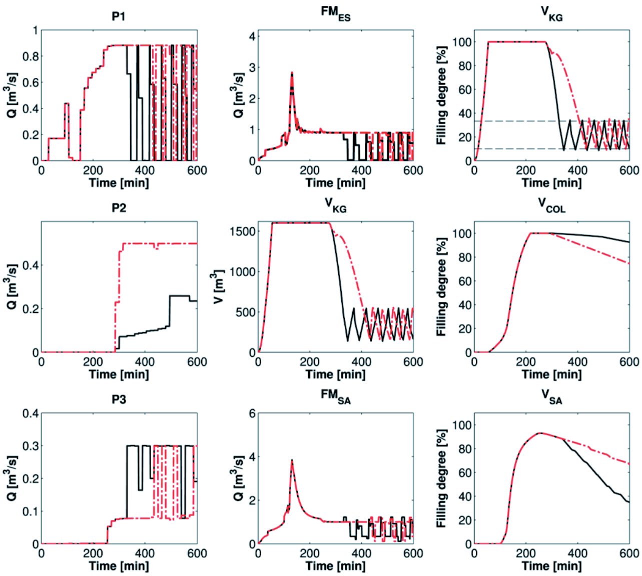

Figure 7: The simulation results with objective function three (F_3) and six (F_6). The black lines are the results with F_3 and the red, dashed lines are the results with F_6.The first column shows the MVs, the second shows the CVs and the third shows the connected volumes.

Based on the results objective function six is chosen for further evaluation.

3.4 *Sensitivity analysis*

3.4.1 Tuning of sampling time versus control horizon

For the control horizon, a lower and upper bound is defined around the nominal value of 15 minutes used in previous simulations. For the lower bound, five minutes is chosen, which is less than the transportation lag-time in the system. The shortest emptying time is related to V_{KG} and is approximately 30 minutes. To this time constant five minutes is added, which corresponds to half of the transportation lag-time related to the actuator in V_{KG}. Therefore the approximated first order time constant of the system is 35 minutes and we have selected 30 minutes as the upper bound for the control horizon. Hence the following scenarios are tested for the tuning of the optimization problem, as the sampling time cannot be larger than the control horizon: $(T_s, \Delta t) \in$ [5,5 ; 5,15 ; 5,30 ; 15,15 ; 15,30 ; 30,30]. The scenarios are run with a CDS rain with a return period of two years (previously used in section 3.2.4), as well as a historical rain event with a similar return period[5].

The results of the simulations of the scenarios are shown in Figure 8.

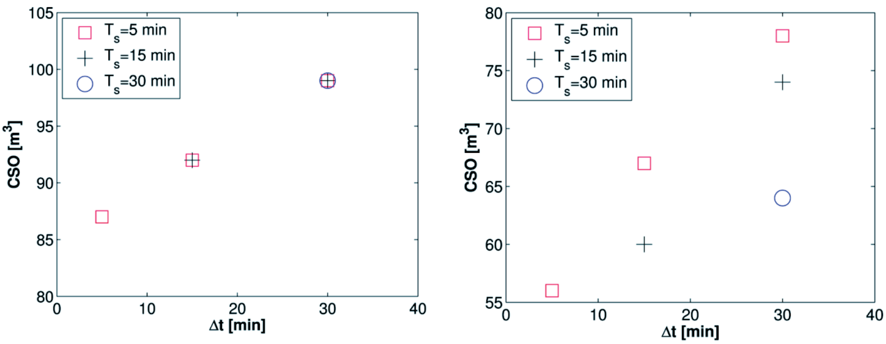

Figure 8: Results from sensitivity analysis of the control horizon, Δt, versus the sampling time, T_s. To the left are the results with the CDS rain as input. To the right are the results with the historic rain event as input.

[5] From The Water Pollution Committee of The Society of Danish Engineers' (in Danish: Spildevandskomiteen (SVK)) rain gauge system, gauge 5740, period: 1979-2013, event: 22-05-2011. The return period is determined based on the maximum mean intensity over 30 minutes.

The results in Figure 8 show that:

- A long control horizon will not improve the optimisation results in this case study. Instead the performance becomes worse as the control horizon increases.
- The performance deteriorates as the difference between the sampling time and the control horizon increases.

The reason the long control horizon will not improve the optimisation results is because the long control horizon has a dampening effect on the fluctuations in the optimum actuator outputs as the optimisation finds the average trajectories over the course of the horizon that yields the best results. However, as rainfall is quickly changing, an average trajectory may have too slow changes, to effectively reject disturbances. To account for this, a setpoint trajectory could be determined instead of a constant setpoint, as done by for example Pleau *et al.* (1996), Cembrano *et al.* (2004) and Fiorelli *et al.* (2013), Courdent *et al.* (2015).

The results of the tuning cannot be generalised to apply for all sewer systems, as they might dependent on specifications of case studies. They do however show the importance of performing such analyses. Based on the results both the forecast horizon and the control horizon are chosen to be five minutes.

3.4.2 Sensitivity of weights

The objective function ($F_6 = F_3 + F_4$) contains two terms, with each their own weight. These weights are pertubated one by one with +/- 20 % and the sensitivity is calculated from eq. 13. As it was discussed in section 3.3 the first term minimizes the overflow, while the second term has the benefit of ensuring a quick emptying of the basins. This should minimise the risk of overflow from coupled events. The sensitivity analysis is performed with a historic, coupled rain event[6]. The results can be seen in Table 7.

[6] SVK rain gauge system, gauge 5740, event: 29-07-2005 to 30-07-2005.

Table 7: Sensitivity analysis of the weights of the objective function.

			w_1			
	UO17	**UO32**	**UO38**	**UO42**	**UO44**	**Total CSO**
- 20 %	0	- 20 %	0	- 20 %	0	- 20 %
+ 20 %	0	+ 20 %	0	+ 20 %	0	+ 20 %
			w_2			
	UO17	**UO32**	**UO38**	**UO42**	**UO44**	**Total CSO**
- 20 %	0	- 20 %	0	- 20 %	0	- 20 %
+ 20 %	0	-20	0	0	0	-25

The results show that is mainly the UO32 that is sensitive and it is to changes in both weights. The negative sensitivities show that the total CSO discharge is less in all the scenarios than in the baseline scenario. Additional effort is therefore put into determining the optimal value for w_1 and w_2. Scenarios are therefore run where $w_1$is changed to 0.1 and 10, while w_2 is kept constant at 1 and the other way around. The results can be seen in Figure 9.

Figure 9: Total overflow volume when simulating the optimisation with different values of $\boldsymbol{w_1}$ and $\boldsymbol{w_2}$.

The results in Figure 9 show that the relationship between the performance of the optimisation and the choice of weights is not one, where the global minimum is easily found. However, the weight of w_1 does not only affects results in terms of the objective function, but also the stability of the output. In Figure 10 the results of the optimisation are plotted, with w_1 = [0.1; 1; 10] and w_2 kept constant at one. The results show that the output for the CVs becomes more stable, as the value of w_1 decreases, since this puts more emphasis on the second term of the objective function, which is designed to minimize fluctuations in V_{KG}. Based on the results in Figure 9 and The results of the sensitivity analysis are very case specific and can therefore not be generalized. However, they do show how important it is to perform such a sensitivity analyses, as it can have a significant effect on the results.

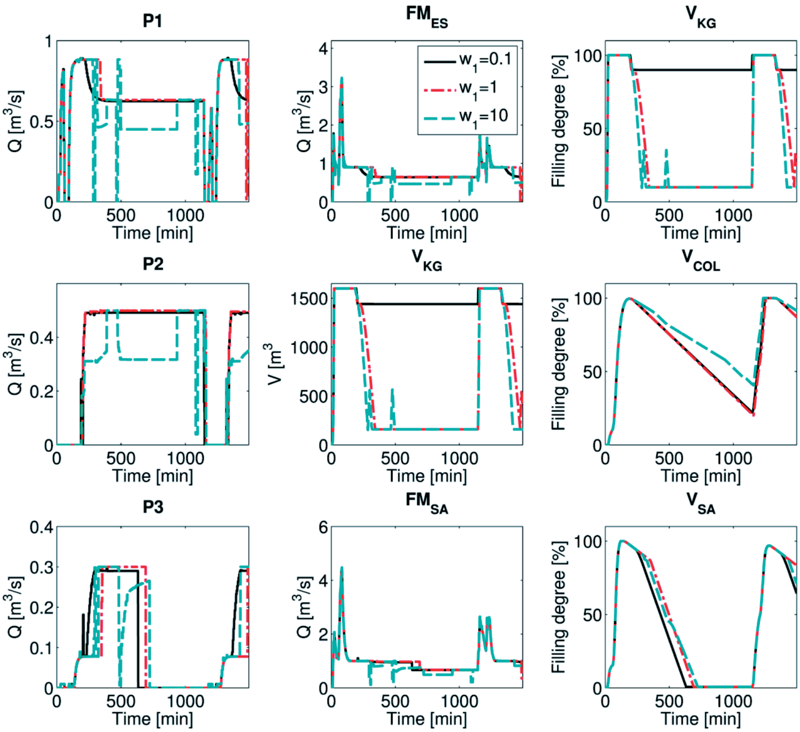

Figure 10: Simulation results from performing the optimisation with varying values of w_1 (0.1; 1; 10), while w_2 is kept constant (w_2 = 1).

3.5 Evaluation

From the sensitivity analysis the best configuration of the optimisation is found to be the following multi-objective formulation:

$$\underset{u}{\operatorname{argmin}} \int_{t}^{t+5\text{ min}} 0.1((FM_{ES} - IC_{ES})/IC_{ES} + (FM_{SA} - FM_{out})/FM_{out}) + ((V_{KG} - V_{KG,max} \times 0.9)/V_{KG,max} \times 0.9) \quad \text{eq. (24)}$$

with a sampling time, T_s, of five minutes.

The objective function minimises the CSO indirectly by maximising the flow out of the system, while limiting the fluctuations in the actuators.

Four different control systems are evaluated, using a one year historic rainseries[7]:

1) The existing control described in section 3.1.1.
2) The regulatory control from Mollerup *et al.* (2015) described in section 3.1.2.
3) Optimising control. The outputs of the optimisation are sent directly to the actuators as control signals as illustrated in Figure 11, left.
4) Control hierarchy with the optimisation acting on the regulatory control layer. The optimum trajectories for the actuators are translated into trajectories for the controlled variables, as illustrated in Figure 11, right.

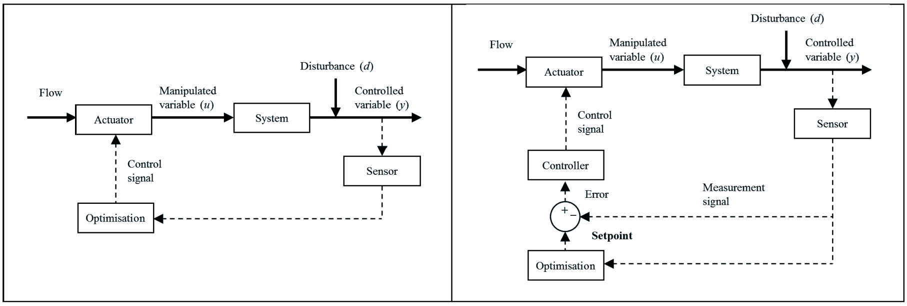

Figure 11: To the left is a block diagram for optimising control. To the right is a block diagram for a regulatory control layer, where the setpoints comes from an optimisation.

However, before performing the rigorous evaluation, the design of the control hierarchy is tested, i.e. the coupling between the optimisation and the regulatory control (the controller in Figure 11, right). This is done with the CDS rain previously used (sections 3.3 and 3.4.1).

[7] SVK, rain gauge 5740, years 2003-2013.

3.5.1 Coupling of the regulatory control with the optimisation

The optimisation can act either directly on the MVs as shown in Figure 11, left, or through the exchange of setpoints for the CVs as shown in Figure 11, right. However, this requires that the pairing between MVs and CVs is given. This was done in a previous work (Mollerup *et al.* 2015) and is shown in Table 3.

To enable the coupling, the output of the optimisation is chosen to be the setpoints for the CVs of the regulatory control layer. These setpoints are fed to the regulatory control layer that will adjust the actuators to keep the setpoint trajectories. The results are shown in Figure 12.

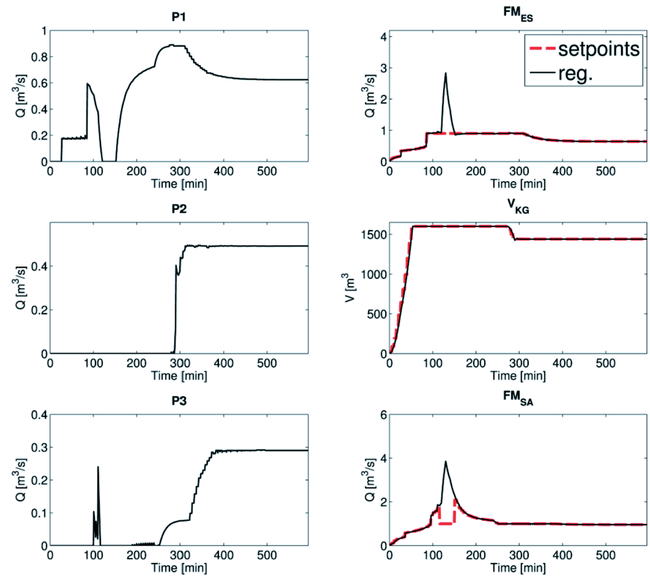

Figure 12: Simulation with the control hierarchy. The left column show the actuators/MVs and the right column show the CVs.

In Figure 12 it can be seen that the setpoints are largely followed, except for a short period of time approximately 120 minutes into the simulation. This is due to the saturation of the controller at the lower limitation; because the disturbances are so large, the controllers cannot fully reject them.

The benefit of having the regulatory control layer is mainly related to the reliability of the control system, as the regulatory control is embedded in the local controllers, while the optimisation is performed at a remote server. Without the regulatory layer in place, the control system is particularly vulnerable to communications failure.

For operators managing the sewer system the presence of the regulatory control will also provide an easy entry point for manual operation, in case of systems failure.

3.5.2 Benchmarking of optimisation and control strategies

Benchmark simulations using one year of historic rain data[8] is performed and the results are compared using eq. 8 and 14. The results are shown in Table 8.

Table 8: Comparison of results (from simulating a one year historical rain series).

	UO17 [m^3]	UO32 [m^3]	UO38 [m^3]	UO42 [m^3]	UO44 [m^3]	Total CSO [m^3]
Existing control	330	3,049	1,993	97	665	6,133
Regulatory control	328	3,282	654	95	626	4,986
Optimising control	331	3,508	912	102	668	5,520
Regulatory control + optimisation	331	3,466	876	107	674	5,455

The results of Table 8 show that the all the proposed control systems improve the performance of the sewer system, compared to the existing control. However, the regulatory control performs relatively better than both the optimising control as well as the hierarchical control system. This can possibly be attributed to the following features of the system design and comparison:

- The tuning of the weights of the objective function. An emphasis had to be made on the stability of the controlled variables, at the expense of the term minimizing the CSO.
- Because of the simplifications made (no noise, evenly distributed rainfall, constant dry weather flow), the coordinating control layer could be designed to fit the system dynamics.

[8] SVK rain gauge 5740, year 2011.

- The size and complexity of the case study is limited. This makes it possible to get the necessary overview of the sewer system dynamics and interactions needed to design the rules of the coordinating control properly using control theory (see Mollerup *et al.* 2015), which is instrumental for the success of the regulatory control layer.

The true potential of having optimisation arises, when a system has many control loops with limiting constraints and/or changing prioritisation between them (Larsson and Skogestad 2000). For a sewer system this can be due to the spatial distribution of the rainfall, changing operating conditions such as dry and wet weather or temporary system changes due to for example repairs. But for small sewer systems with few actuators, a simple SISO control system is often enough (also called local control (Schütze *et al.* 2004b)). With a fine tuning of the weight the optimisation might still be able to perform slightly better or at least as well as the control system with the coordinating control. However, the results show that for small sewer systems, where the complexity is limited, it is not necessarily the best option to implement advanced optimisation based control systems. For future design of optimisation and control of sewer systems, it is therefore rather important to follow a systematic and structured approach in screening and testing of solutions from simpler to more advanced techniques.

4 CONCLUSIONS

A methodological approach has been used successfully to obtain an optimisation for sewer system control. The following focus areas were systematically tested and evaluated:

- The first focus area was the choice of process model. The results showed that in choosing the model, the focus needs to be on both the computational time as well as the needed level of detail, which can be contradictory requirements. The results also showed that if a reliable forecast cannot be obtained, frequent model updating is necessary, as the model predictions will otherwise be useless.
- The second focus area was the objective function formulation. The results showed that formulating the objective function as a direct minimisation of the CSO is not necessarily the best option, since the objective function formulation was only relevant when overflow was predicted or occurring. The alternative of using even filling degree had the problem that it had the opposite effect, when the majority of the tanks were full, since then there was

nothing driving the emptying of the basins. Maximising the amount of treated wastewater, resulted in the best performance. However, an unwanted interaction between the actuators occurred that could only be solved by using a multi-objective.

- The third focus area was a sensitivity analysis and tuning of the optimisation parameters. A tuning of the sampling time and the control horizon was performed. The results showed that a long control horizon did not improve the optimisation results in this case study. Instead the performance became worse as the control horizon increased. This was because the long control horizon had a dampening effect on the fluctuations in the optimum actuator outputs and therefore the disturbances were not rejected as efficiently as with a short control horizon.

  The weights of the multi-objective function were also analysed. The sensitivity analysis showed that the total CSO volume was sensitive to the weights. However, the final choice of the weight was based not only on the benchmarking metric (in that case CSO), but also the stability of the controlled variables and thereby the actuators, since a stabile operation of the actuators is also a key performance indicator and desirable from system maintenance and economics point of view.

Finally the optimisation was evaluated with a one year historic rain series. The performance was benchmarked against the existing control, a regulatory control system (with setpoints coming from a rule based coordinating control layer) and with the optimisation acting on the regulatory control layer. The results showed that all three control systems performed better than the existing. However, the best performance came from the regulatory control with setpoints coming from a coordinating control layer. This suggests that for small sewer systems, like this case study, regulatory control can be as effective a strategy as the more advanced optimisation strategy. Hence, for the design of sewer system control, it is important to systematically test from simpler to more advanced strategies.

5 ACKNOWLEDGEMENT

The authors would like to sincerely thank Dr. Niels Bent Johansen for his participation and contribution to inspirational discussions on sewer system control.

This project is initialized and financed by HOFOR and BIOFOS and is financially supported by The Danish Agency for Science, Technology and Innovation under the Industrial PhD program (project number 11-109494). The support is greatly acknowledged.

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SUPPLEMENTARY MATERIAL

Model 3

In model 1 the majority of the inflows to the real tanks where unmeasured and therefore unknown and assumed to be zero in the optimisation. In this model the inflows are estimated from the runoff model and this is in turn used to calculate the inflows to the real tanks and the intermediate flows of the system.

$$V_{KG}(t_0 + \Delta t) = V_{KG}(t_0) - P_1(t) \times \Delta t + P_2(t) \times \Delta t + q_1(t) + q_2(t) \quad \text{eq. (A.1)}$$

$$V_{COL}(t_0 + \Delta t) = V_{COL}(t_0) - P_2(t) \times \Delta t + q_6(t) + IO_{KG}(t) \quad \text{eq. (A.2)}$$

where $IO_{KG}(t)$ is calculated from:

If

$$q_1(t) + q_2(t) + P_2(t) > P_{1,max}$$

Then

$$IO_{KG}(t) = q_1(t) + q_2(t) + P_2(t) - P_{1,max} \quad \text{eq. (A.3)}$$

Else

$$IO_{KG}(t) = 0$$

$$V_{SA}(t_0 + \Delta t) = V_{SA}(t_0) - P_3(t) \times \Delta t + IO_{SA}(t) \quad \text{eq. (A.4)}$$

where If

$$\min\left(\min\left(q_3(t) + P_1(t); FM_{ES,max}\right) + q_4; FM_{AH,max}\right) + P_3(t) + q_5(t) > FM_{out,max}$$

Then

$$IO_{SA}(t) = \min\left(\min\left(q_3(t) + P_1; FM_{ES,max}\right) + q_4; FM_{AH,max}\right) + P_3(t) + q_5(t) - FM_{out,max} \quad \text{eq. (A.5)}$$

Else

$$IO_{SA}(t) = 0$$

$$FM_{ES}(t + \Delta t) = P_1(t) + q_3(t) \quad \text{eq. (A.6)}$$

$$FM_{SA}(t + \Delta t) = P_3(t) + q_5(t) + IC_{AH}(t) \quad \text{eq. (A.7)}$$

where

$$IC_{AH}(t) = \min\left(\min\left(q_3(t) + u_1(t); FM_{ES,max}\right) + q_4; FM_{AH,max}\right) \quad \text{eq. (A.8)}$$

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